SYSTEMIC APPROACH TO IMPROVE LEARNING FROM INCIDENTS

A Thesis

by

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Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

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May 2017

Major Subject: Safety Engineering

ABSTRACT

Learning from incidents has always been very challenging for industry and regulators due to the associated complexity in human and organizational behavior. In spite of the efforts and resources spent on incident investigation processes and organizational learning techniques, the outcome has not shown a significant improvement. Chemical process incidents such as Texas City Refinery explosion, T2 Laboratories explosion, and West Fertilizer explosion continue to occur. It is evident that as an industry, organizations are continually failing to learn from the past incidents. The question is if organizations are ready to learn, are they following the right learning approach? Organizations should adopt a systemic learning approach where the collected knowledge is leveraged in order to enhance the performance of the safety management systems and consequently prevent future incidents. The objective of this research is set to enhance our understanding on how a company and the industry as a whole learn from past incidents and define the key elements to improve the systemic learning. This study was divided into four main phases: identification of the learning system, development of a learning process and a proposed incident investigation process and finally the validation of the proposed incident investigation process through a case study.

First, the learning system for the chemical and oil and gas industry, the different types of learning, and the entities involved in it has been characterized. Based on the results, some limitations on the system were identified and discussed. Secondly, a systemic process for improving learning from incidents has been developed based on the

identified limitations of the learning system. The proposed process provides a holistic view of the learning process and explored the concept of knowledge management into safety systems. Likewise, it provides guidelines of how learning systems can be executed within the organization and how to support the implementation of safety knowledge inside of it. Third, an incident investigation process has been proposed to provide additional sources of information into the analysis, in order to support the identification of root causes and the required changes in the management systems of the organization. The process that has been developed enhances understanding of how to get information and transform it into valuable recommendations that can be implemented in their processes. Finally, the proposed process has been explained through a case study. The obtained results provide a clear picture of how an incident investigation report can be enhanced through this process.

DEDICATION

To

My parents: Samuel Guarguati and Martha Ariza, and

My boyfriend: Gabriel Ortiz,

for all your love and support.

ACKNOWLEDGEMENTS

First of all, I would like to express my sincere gratitude to my advisor and mentor, Dr. Sam. Mannan. His guidance and continuous support gave me the confidence to aspire and continually push myself to accomplish goals in my professional career. I also want to thank him for giving me the opportunity of being part of the Mary Kay O'Connor Process Safety Center at which I had the opportunity to meet inspiring and wonderful people who taught me and supported me during this journey. I also would like to thank my committee members, Dr. Mahmoud El-Halwagi and Dr. Peres, for taking their time to serve on my committee. Especially, I would like to thank Dr. Peres for her guidance, support, and the time we spent together trying to make this real.

I want to thank Dr. Noor Quddus for his support in all stages of my research. His supervision, constructive comments and suggestions helped me shape this thesis. I am also thankful to Valerie Green for all her administrative support, patience, and personal guidance when I needed them. In addition, I want to extend gratitude to my sponsor Colfuturo for providing me the financial support to accomplish my dream.

I also want to thank my friends at Texas A&M University for all the special moments we spent together. I am grateful to my boyfriend for all his support and the happiness he brings to my life. Finally, I would like to thank my parents who made my dream real, for motivating me to be a better person, and their unconditional love, guidance, and support.

CONTRIBUTORS AND FUNDING SOURCES

This work was supervised by a dissertation committee consisting of Professor M. Sam Mannan [advisor and chair] of the Department of Chemical Engineering and Professor Mahmoud El-Halwagi of the Department of Chemical Engineering and Professor S. Camille Peres of the Department of Public Health. All work for the dissertation was completed independently by the student.

Graduate study was supported by the Harry West fellowship from Texas A&M University and the sponsor COLFUTURO from Colombia.

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1. INTRODUCTION

1.1. Motivation

In the chemical and oil and gas industry, organizations and regulators have spent a significant effort into incident investigation processes and organizational learning techniques in order to improve continually, avoid the same mistakes, and consequently prevent incidents. In spite of these efforts, the outcome has not shown a significant improvement and process safety incidents continue to occur. According to the Bureau of Labor Statistics [1], over the five years period from 2010 to 2014, there were 758 fatalities in the chemical and oil and gas industry (the statistics covers the following sectors: manufacturing, oil and gas extraction, drilling oil and gas wells, support activities for oil and gas operations, and petroleum refineries) [1]. Likewise, in 2014, an estimated 46,200 nonfatal injuries and illnesses were reported [1]. These statistics suggest that the industry as a whole is failing to learn from the past incidents. Learning from incidents provides organizations the required knowledge to improve safety management systems and prevent future incidents, by understanding what went wrong in past incidents, analyzing their lessons learned and implementing the necessary changes into their processes.

During the last three decades, the industry has seen significant process safety incidents that have been precursors of changes in regulations and standards in United States and the rest of the world. However, there is a failure to successfully implement and enforce those changes and make them transcend over the years. Thus, process safety incidents become part of the history and the industry is doomed to repeat the same mistakes. Without doubt, no process safety incident has been as harmful as Bhopal disaster in 1984, due to the enormous impact in terms of fatalities, financial losses, environmental damage, and industry reputation. This incident made organizations realize the importance of learning from incidents not only inside the organization, but also learning from external incidents that may be applicable to their operations. While no other incident has been as devastating as Bhopal incident, there have been several disasters over the last decades that have had significant impact on the industry and from which the same mistakes can be identified over and over again.

During the same year as Bhopal disaster, in San Juan, Mexico City a catastrophic fire and series of explosions at an LPG terminal killed over 500 people, injured 7,000 and more than 200,000 people were evacuated [2]. The day of the incident, LPG leaked from a pipeline rupture, which formed a vapor cloud that dispersed into the surrounding for about 10 minutes. The vapor cloud ignited and a flash fire resulted causing a violent shock, resulting in a series of BLEVEs and minor explosions in nearby houses and facilities in the area [3]. Some of the causes and contributing factors of this incident were that no hazard identification process was carried out for the unit and there was a lack of awareness regarding the associated hazard not only from the organization but also the community and the emergency responders. Likewise, there was a lack of effective land use planning due to the lack of regulations to control the construction of residential houses around the facility. In addition, the incident showed an inadequate mechanical integrity program as one of the root causes of the incident. Moreover, there was a lack of emergency response planning and training regarding hazard identification. Due to the substantial impact of this incident, the same causes and contributing factors were expected to be learned collectively within the organization. However, this organization reveals a failure to learn from its own history. The safety performance of the organization over the last ten years exposes an estimated 197 incidents and 21 fatalities per year [4, 5]. In these process safety incidents mechanical integrity, inadequate land use planning, and inadequate emergency response were identified as contributing factors.

Similarly, process safety incidents such as West Fertilizer explosion (2013) in which a fire and explosion of ammonium nitrate killed 15 people including 12 emergency responders, injured more than 260 people and severely damaged the nearby community [6]. Another incident, Tianjin explosion (2015) in which a series of explosions in a warehouse killed 173 people, 110 of them first responders, injured more than 797 people and damaged around 17,000 houses [7]. In both incidents, the same contributing factors as Mexico City disaster such as poor hazard awareness, inadequate land use planning, and inadequate emergency planning were identified. Even though these incidents do not have the same causes as in Mexico City incident, it is evident that the same contributing factors increased their severity. Both examples illustrate a lack of organizational memory and an inability to effectively share and implement lessons learned.

As can be seen, organizations have failed to recognize and learn effectively from past process safety incidents. In addition, the knowledge that is embedded into those incidents has been lost over the years, making it difficult for new generations to understand the reasons behind the implementation of those lessons learned. The incidents showed in the previous examples reflect a lack of an effective management system, which enables organizations to learn, adapt and grow [8]. This suggests having an effective learning system that serves as a source of knowledge by the acquisition of relevant information, the analysis of it and the use of this information to improve and prevent process safety incidents. The question is if organizations have the required information, are they following the right learning approach? Organizations should adopt a systemic learning approach where the collected safety knowledge is leveraged in order to enhance safety management systems and make the lessons learned part of their culture.

1.2. Background

The study of how organizations learn from incidents and manage safety to prevent process safety incidents is not a new topic within the process safety research area. However, this field has gained more attention during the last sixteen years and more disciplines such as psychology, sociology, and engineering have been studying it. As a result, learning from incidents has become a fragmented field in which different approaches have been proposed for specific scenarios or situations such as a certain part of the learning process, the group of interest or the industry in which it is applied. Back in the 70s, the theory on organizational learning proposed by Argyris and Schön highlighted the importance of learning to detect and respond to undesirable events [9].

The theory suggested two modes of learning: single and double-loop learning. Even though, both modes of learning are necessary, the authors emphasized the importance of achieving double-loop learning to identify organizational and systemic failures [10]. This theory is still accepted and has been widely recognized in this field despite current advances in organizational learning theories [11]. Lukic 'research supports this theory by the analysis of the type of learning that is adopted in organizations, in which incidents usually are a combination of technical, human, and organizational factors, making single and double-loop essential factors to accomplish successful learning [12]. Likewise, Choularton demonstrated how double-loop learning could be to avoid superficial learning [13].

Over the years, learning from incidents has been categorized into several areas of study such as lessons learned, incident investigation and analysis, learning from incident process, and conditions for learning [11]. Kletz has been one the pioneers of introducing lessons learned from process safety incidents into organizational systems and introducing real examples of how organizations failed and how to overcome these types of failures. Furthermore, the author discussed how organizations have no memory and the need to share and implement lesson learned [14, 15]. Aligned with this author, several studies have also suggested that significant improvement have been made in the development of lessons learned. However, the dissemination and implementation of lessons learned inhibit the complete learning process [16-18]. Moreover, the literature provides guideline of how to develop lessons learned, how to enhance the dissemination process and how lessons learned can be embedded into the organization [17].

Incident investigation and analysis represents one of the most critical steps in the learning process due to the challenges that may arise from the identification of root causes in process safety incidents. Lukic stated the importance of identifying appropriate approaches to analyze incidents depending of the complexity of them and provided solutions within the proper domain [12]. Similarly, research by Lindberg, Hansson and Rollenhagen explored the literature with respect of incident investigation process and proposed the CHAIN model based on six basic criteria for incident investigation. The model argued the importance of studying the effectiveness and effects of different incident investigation methods in order to apply appropriate techniques and improve the experience feedback process [19]. In the same context, Fahlbruch and Schöbel presented the Safety through organizational learning (SOL) method in which a standardized process for analyzing incidents in a holistic socio-technical approach have been proposed to support incident investigation analysis [20].

Regarding learning from incidents processes, several frameworks have been proposed with the objective of increasing effectiveness in learning. Lukic proposed a framework for development of learning initiatives in organizations. The framework identified five elements that organizations should analyze to select the appropriate approach for learning: participants, learning process, type of incident, type of knowledge and learning context [21]. Although the framework proposes valuable initiatives, it does not identify how its initiatives are linked to a system that can be implemented in organizations. Similarly, Coze proposed a framework that integrated the different approaches from which learning have been analyzed. The framework provided a bigger picture of this field and highlighted the main elements that influence learning such as actors, countries, steps, industry, disciplines and intensity of the event [22]. Conversely, semi-quantitative studies have been conducted to determine the expected behavior of learning from incidents within an organization over time. Cooke proposed a model to show the dynamic of the system, how each element operates and serves as a continuous improvement process. The model also suggested how incident-learning systems serves as a bridge between accident causation theory and high reliability theory [8]. Likewise, Avnet analyzed the expected behavior of shared knowledge over time by the validation of share knowledge networks within the offshore oil and gas industry [23].

Literature regarding condition for learning described relevant factors that influence the effectiveness of learning processes. Conditions such as trust, culture of no blame, people involvement and information availability have been identified as necessary conditions to increase reporting and enhance learning [11, 24]. In this context, studies explored the potential impact of learning at multiple levels and the need of better tools for incident investigation analysis [25]. Likewise, the literature emphasizes the need to create resilience organizations in order to been able to adapt to and absorb changes once an incident occurred [26]. In the same way, studies suggested the need of involvement of new groups of experts to incorporate new insights into the field of learning [27]. With respect to learning effectiveness measures within organizations, Jacobson presented a method for evaluating the level of learning in terms of how broadly the lessons learned are implemented, how much the organization is involved in this process and for how long the lessons learned last within the organization [28]. Similarly, studies suggested different learning criteria to analyze and identify potential areas of opportunity within the learning process [29, 30]. Finally, Naot proposed a method to analyze the effectiveness of organizational learning after an incident occurred. The method incorporated twenty-two performance indicators of the learning process, which determines the quality of the organizational learning system within the organization [31].

1.3. Objectives

This research aims to develop a comprehensive approach to integrated the main stages of the learning process and enhance incident investigation processes. This is done with the objective of providing a holistic and systemic view of the learning from incidents process and exploring the concept of knowledge management into safety learning systems. This research incorporates a psychology and engineering viewpoint in order to provide an overall analysis of learning systems in the chemical and oil and gas industry. Moreover, it provides more insights into the implementation of learning systems within the organization. In this context, the specific objectives of this research are:

- Identify the limitations in the learning system for the chemical and oil and gas industry and provide recommendations to guide organizations on how to overcome the identified limitations on the learning system.
- Enhanced understanding of how to learn form process safety incidents and how to develop learning from incidents systems that enable organizations to improve

internal learning. Additionally, to identify the key elements organizations should take into account to improve this learning.

- Develop a framework to determine how organizations can improve the internal learning process and transferring knowledge. It will provide a systemic approach to improve learning from incidents and will serves as a guideline for organizations on how corporate learning systems can be executed within the organization and how to support the implementation of safety knowledge inside of it.

1.4. Thesis organization

This thesis involves four main phases: identification of the learning system, development of the learning process, development of a proposed incident investigation process and finally the validation of the proposed incident investigation process through a case study.

The first phase reviews the organizational learning theory and relevant concepts for the development of the following sections. It also discusses the barriers that inhibit organizational learning, factors that influence learning, and the different types of learning methods that organizations can apply. Moreover, reviews the incident investigation terminology and process. It also provides a general description of some relevant incident investigation methodologies. Finally, this phase discusses the learning system and the limitations that can be identified on it.

The second phase of this research introduces the proposed learning process and examines each element of it. It also shows how a corporate learning system should operate and the key elements that organizations needs to take into account during its implementation.

The third phase of this thesis introduces a more detailed analysis of the first step in the proposed learning process: enhance internal information. It examines the incident investigation process and methodologies throughout the development of a task analysis and a comprehensive analysis of the current incident investigation process. It also presents the proposed incident investigation process and provides a description of each of the incorporated steps.

Finally, the last phase analyzes an incident that occurred in the offshore industry in North America. The incident has been examined through the proposed incident investigation process showed in the previous section. The analysis comprises the analysis of two external incidents with similar causes and three internal incidents that occurred in the same organization. It should be noted that the incident investigation has been performed by the organization at the time where the incident occurred. Therefore, the objective of this analysis is to identify improving opportunities of the final report through the analysis of similar incidents in the industry. The explained methodology is presented in Figure 1.

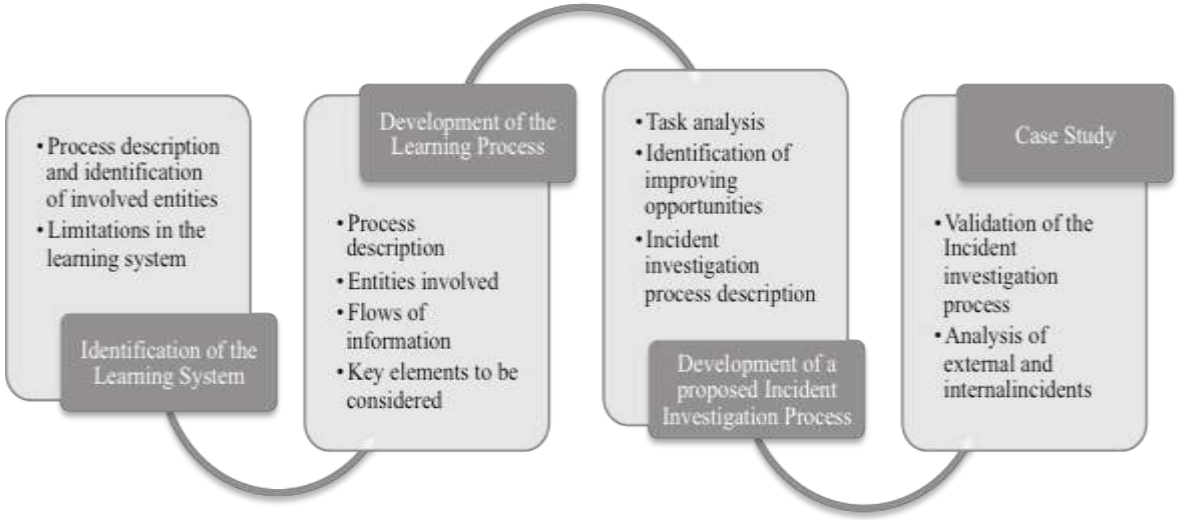

Figure 1 Thesis methodology

2. ORGANIZATIONAL LEARNING

2.1. Organizational learning

Organizational learning needs to be understood from the social and systemic perspective, since it emerges from the internal and external interactions among individuals, technology and cultures. Thus, learning is not limited to the acquisition of technical knowledge; it also requires the analysis and interpretation of the context where the knowledge is going to be applied, and the understanding of human behavior and social interactions that emerge in an organization [32]. As a result, this field has been very challenging for the academia and industry, since the outcome is always going to be different from organization to organization and even in the same organization, among generations. Then, the real challenge is to transcend from the individual to the organizational learning, in order to ensure that the knowledge has become part of the culture of the organization regardless the people that are part of it. Individual learning refers to the enhancement of individual mental models, through the acquisition of new or modified knowledge, which subsequently guide human behavior and decision-making [33]. Once the individual learning is achieved, this knowledge has to be stored, communicated and implemented through the organization, so it can be available and easily retrieved once it is required by another person, and consequently ensure organizational learning.

Organizational learning is explained based on the individual learning theory, in which learning is shown by the accumulation of individual learning that is reflected as routine actions and values on behalf of the organization [33]. Therefore, individual learning set the foundations of this theory, and then the organizational components are added to gain a better understanding of the expected outcome. As stated by Fiol and Lyes, organizational learning can be defined as a "change in the organization's knowledge that occurs as a function of experience" [34]. Likewise, in the technical view, organizational learning is described as "the effective processing, interpretation of, and response to, information both inside and outside the organization" 1999 [32]. Finally, as assert by Huber, "an entity learns if, through its processing of information, the range of its potential behaviors is changed… an organization learns if any of its unit acquires knowledge that it recognizes as potentially useful to the organization" [32, 35] . Based on the previous aforementioned, it can be concluded that organizational learning is the process in which the knowledge is acquired for both outside and inside the organization, is organized, analyzed and finally, applied in the organization. Moreover, it is expected that this learning, changes human behaviors and gain experience for the organization.

Learning is a continuous process and varies depending of the size of the 'unit' that is getting the knowledge, *i.e.* employee, a department or an industry. Thus, organizations gain knowledge in the following units of learning: individual, groups, organizations, and inter organizations [36]. This learning is incremental as shown is Figure 2. Individual and organizational learning have already explained in the previous paragraphs. However, between them, the group learning is present, which refers to a group that gains knowledge together through the interaction and experience with another individual [37]. As an example of group learning we can identify a group people from different departments, sharing the lessons learned from case study. On the other hand, organizational learning is not the ultimate goal to understand the learning system as a whole. The final level of learning is the inter-organizational learning, in which different organizations share, communicate and learn together from experience. For the purpose of this research this type of learning refers to the industry learning, more specifically, the chemical and oil and gas industry learning.

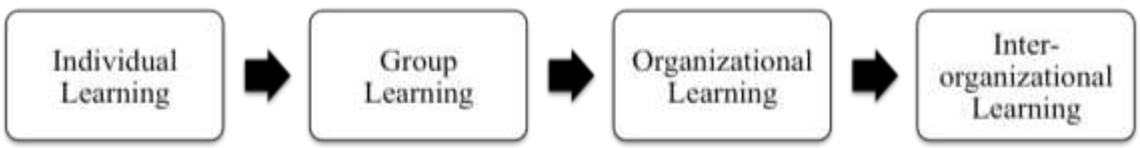

Figure 2 Units of learning

2.2. Single and double loop learning

Learning from experience is also explained based on the concepts of single-loop and double-loop. This model is based upon "theory of action" and "theory of use", developed by Argyris and Schön [38]. The model stated how people act based on their mental maps and therefore how they plan, execute and evaluate their actions [38]. These theories suggested three elements or stages of the learning experience, as shown in Figure 3.

- *Governing variables* describes why people do what they do. Those are the main values, beliefs and conceptual frameworks that are rooted to their cultural background [39].
- *Actions* describe what people do. Actions are the plans and strategies used by people according to their governing variables. These strategies are executed in order to keep their governing variables within acceptable limits [39].
- *Results* describe the consequences or what people obtain from their actions. These results can be both intended or unintended [39].

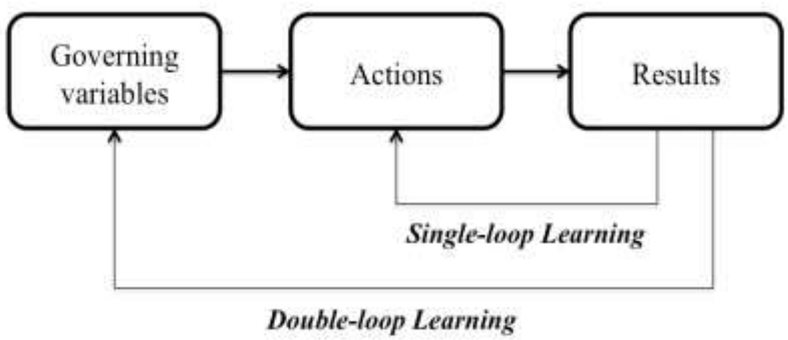

Figure 3 Single-loop and double-loop learning, adapted from [39]

Single-loop refers to the learning process in which the actions are modified based on the expected results or consequences obtained. This type of learning involves the recognition of an undesired outcome and the modification of the actions that leads to it. It also can be defined as the correction of an error by changing the strategy of actions. In the single-loop learning the governing variables remain unchanged. Conversely, double-loop learning requires an additional step in which the governing variables are questioned and evaluated in order to develop changes from the values, policies and objectives of the organization [39].

The literature suggested that most of the organizations act according to single-loop learning [40], in which operators spend their time focusing on how to correct immediate actions to avoid the same mistake. But no actual analysis is performed to detect the root causes of the incident and consequently, determine if a change in the system is required or not. On the contrary, double-loop learning requires organizations to develop critical thinking, in which subject matter experts should analyze the situation and challenge the existing rules governing the organization. In conclusion, double-loop learning allows organizations to identify root causes instead of intermediary causes and therefore, prevent recurring in the same type of incidents. Moreover, single-loop learning can limit organizations to only solve the symptoms of the actual organizational causes.

2.3. Organizational processes

2.3.1. Knowledge

Knowledge is the outcome of learning [41]. Knowledge is defined as the transformation of information, in which expert opinion, skills, and experience have been accumulated. Knowledge is the synthesis of multiple resources of information over time, in order to understand patterns and support decision-making [42, 43]. Thus, the organizational learning objective is to enhance the knowledge that is acquired by the employees and make sure that this knowledge is successfully stored and transferred among the whole organization.

Knowledge can be categorized into two forms: explicit and tacit knowledge. Explicit knowledge refers to what people knows and can be explained by individuals. This type of knowledge is relatively easy to store, identify, and retrieve [44, 45]. Explicit knowledge transfer can be verbal or written. Examples of explicit knowledge are reports, procedures or case studies. The challenge with this type of knowledge is to ensure the availability of the information as needed [46]. In contrast, tactic knowledge refers to know-how [45, 47]. This type of knowledge is personal in nature; this implies that the knowledge remains in the heads of individuals that are part of the organization. Therefore, tacit knowledge is hard to extract and is mostly experience based. Tacit knowledge can be transferred through training, practices, and experience [46]. Examples of tacit knowledge are the skills and expertise acquired by an employee or the values and cultural beliefs of an employee.

2.3.2. Knowledge transfer

Knowledge transfer is no longer considered as an act [48]. Instead, it is considered as a process in which, organizations gather valuable information and experiences from one entity to another, within the organization and among them [49]. Those entities can vary depending of the number of people involved, such as groups, departments, and facilities. The challenge with transferring knowledge is to transcend from individual level to higher levels, in order to ensure that knowledge has been implemented through the organization. Moreover, assessing how effectively organizations are transferring knowledge is a difficult task, due to the complexity of measuring changes in knowledge and performance of the recipient entity [50].

Transferring knowledge in organizations required the combination and interconnection among three elements: members, tools, and tasks. By combining those elements through the process, organizations can create knowledge management system, where the knowledge can be stored in the organization through generations.

The process of transfer knowledge starts with the externalization, in which the person or team must find the best method or approach to deliver the knowledge they want to transfer. In this stage, the tacit knowledge has to be converting into explicit knowledge so it can be delivered verbally or in written form. Second, the integration, in which the knowledge is adapted and analyzed based on the context where it is going to be applied. Finally, internalization, in which, the new knowledge is applied and incorporated into the system [51, 52]. However, this process does not ensure that the transfer knowledge is going to be successful.

Additionally, there are barriers involved in the process that makes it more complex and therefore, makes the expecting outcome unpredictable in some cases. Some of those barriers are explained below:

- *Receiver of the knowledge:* the effectiveness of the transfer process depends on who the intended receiver are, how familiar they are with the knowledge they will get, and the context where it is applied. The similarity of task and context between the transferring entity and the receiver entity determines how complex the process and the type of technique they should implement. Likewise, it is important to understand the background of the receiver, in terms of the experience and technical knowledge that they have, in order to define the best approach to deliver the knowledge [52].

- *Nature of the task:* another barrier that involved in the process is the nature of the task, referring to how frequent a task is performed and if the task is a routine or not activity. The nature of the task enables us to understand how familiar the employees are with it and the type of system they are approaching [52].
- *Type of knowledge:* the complexity of the process differs significantly depending of the type of knowledge that will be transferred. The knowledge can be tacit or explicit knowledge, and as mention before, explicit knowledge is easier to communicate than tacit knowledge [52].

2.3.3. Organizational memory

Improving learning from incidents within an organization means improving the organizational memory. Past incidents acquired by individuals become the source of knowledge and is then analyzed, stored, and retrieved as a form of experience gained by the organization as a whole. Improving the organizational memory of an organization can increase productivity, decrease costs, and generally improve the know-how of the organization due to accumulation of knowledge, implementation of new ideas, and correction of errors, and consequently, lead to improve decision-making within the organization.

Organizational memory is defined as the knowledge from the past that is exerted upon present organizational tasks and routines [41, 53]. Likewise, organizational memory is seen as the stored knowledge that an organization possesses [41]. This concept has been evolving over the years, changing the approach and techniques applied to gain and retain knowledge within the organization. The main change resides in the evolution from individual memory to a corporate memory, with respect of the place where the knowledge is stored. Nowadays, the objective is to enhance the mechanisms in which knowledge is stored so it can be easily extracted through the years and organizations do not have to rely only on individuals to maintain knowledge. These mechanisms of storing are employees, organization's culture, procedures and routines, the management system, and the physical structure of the workplace [41]. The combination of all of these mechanisms, ensure that organizations implement the knowledge and make it part of the daily activities in the organization.

As Walsh and Ungson states, the organizational memory process involves three stages: acquisition, retention, and retrieval [54]. The acquisition occurs when new information is gained based on decisions and the evaluation of the consequences of those decisions. The accumulation of information based on past decisions refers to the organizational memory that is acquired by the organization [54]. Then, the information is retained by the different storing mechanisms that the organization possesses, in order to disseminate and implement the information across the organization. Finally, organizations have to ensure that information can be retrieved as required. Thus, employees can access the stored knowledge throughout the whole organization.

2.3.4. Organizational forgetting

Do organizations retain all the knowledge they get over the years? Does knowledge change over time? Since employees leave, the technologies and best practices change, and all the information cannot be retained. It is important that organizations take into account the depreciation of knowledge over time and the amount of knowledge that is forgotten by the organization once employees are no longer part of it or whenever a new process is implemented.

Organizational forgetting is the intentional or unintentional loss of knowledge at any level within an organization [55]. The intentional forgetting refers to process by which individuals discard obsolete knowledge in order to receive updated or new knowledge. By doing that, organizations are able to adapt to new changes in the environment. Intentional forgetting is also called as unlearning process. Conversely, the unintentional forgetting refers to the degradation of knowledge over time, due to lack of storing mechanisms within the organization. Studies suggests that organizational forgetting can be seen as positive and negative as the same time, considering unlearning as the process that helps organizations to adapt and stay competitive in the market. In contrast, it can be seen as negative when forgetting occurs with no reason and prevents organizations to remember what need to be done to avoid the same mistakes [33, 55].

2.4. Barriers of organizational learning

The learning process becomes more complex for organization than for individual due to a number of internal and external difficulties that inhibit organizations to learn appropriately. Consequently, organizations have to focus their attention not only in the elements that affect individual learning. They also have to understand the complexity of learning interactions among individuals and the external elements that limit the learning process. This research has been focusing in the understanding of eight barriers that prevent or reduce the learning outcome:

- *Ambiguity about incident causation:* refers to the tendency of the top management level to select one interpretation instead of another. That means, that a leader is going to choose to learn only from what it is familiar to him, and is aligned with their preconceptions, actions, and goals [56] . This type of barrier, limited the amount of lessons learned that are going to be communicated and implemented within the organizations. Likewise, in some cases, this type of barrier can lead organizations to interpret lessons learned incorrectly.
- *Political environments:* refers to the limitations experienced by organizations once an incident occurred. In which, the quality of the recommendations are going to exposes the self-interests of some people. In this sense, the recommendations are going to blame someone instead of pointing out failures in the management system and consequently in the top-level management [56]. Moreover, political environments restrict the amount of information that is communicated through the organization and among them. In such politicized environments, learning is reduced to a limited amount and low quality of lessons learned and partial learning within the organization.

- *Competitive organizations:* refers to the restrictions and limited knowledge that is shared between and within the organizations. Learning is limited to the knowledge and experience that is created inside the facility or organization. People from one facility may not know what another facility is doing in terms of safety in order to prevent the same mistakes. Competitive organizations are one the major barrier that the chemical and oil and gas industry is facing nowadays. Sharing lessons learned is restricted by lawyers inside and outside organizations, due the expose of sensitive information that can reveal the know-how of organization. The chemical and oil and gas industry needs to learn from industries such nuclear and aviation, in which the information is shared among the whole industry to improve together and prevent future incidents [56].
- *Lack of leadership:* the role of leadership is key for organizations in order to learn and have an open environment that helps employees to raise their concerns and suggestions about how things are running. Leaders need to be involved in the learning process, to motivate and support people throughout the process and give them the required resources to achieve the expected outcome. Thus, leaders are responsible for giving employees the spaces to learn and high quality resources to get the appropriate knowledge. Additionally, leaders have to be shown as an example, being committed to their own learning process [57].
- *Unlearning process:* unlearning refers to process in which individuals discard obsolete knowledge in order to receive updated or new knowledge [33]. This process requires a high degree of reflection and understanding of what need to be

changed, making this process challenging for organizations because some people are resistant to changes, act on the defensive, and have their own prejudices. Therefore, organizations have to be creative, intuitive, and patients to face this process [57].

- *Organizational culture:* working in the culture of the organization is a continuous journey in which all employees need to be engaged with the organization and they have to believe the values and goals of the organization. A good organizational culture allows companies to build trust among employees, motivate them to receive knowledge from others and learn individually, in groups and in organizational level. Furthermore, it helps organizations to be open to changes, innovation and admission of mistakes when required. Finally, it increases near miss reporting, since a culture of no blame is encouraged [50].
- *Inadequate communication:* refers to the different communication channels that an organization has and how much of their knowledge they are willing to share. This also applies to the internal communication between departments and facilities. If an organization is open to communicate and share their previous experiences and knowledge, they can also receive knowledge from others and therefore, avoid the same mistakes. Likewise, organizations have to ensure open spaces in which the internal knowledge can be transferred from one facility to another. Finally, leaders have to ensure an open environment in which employees feel free to communicate with them to provide suggestions and receive feedback from their job.

- *Short-term focus:* refers to the tendency of some organizations to focus their effort in solving short-term problems instead of looking at the big picture. Most of the recommendations from incidents tend to focus just in the intermediary causes. Thus, the management system failures remain hidden and the real problems are not analyzed. This happens because root causes require more time to be identified and addressed, and it requires a higher level of commitment for the top management level. Similarly, this type of barrier refers to the tendency to focus in the single-loop learning in which only actions are modified but no analysis of the root causes is performed.

2.5. Learning methods

Knowledge is delivered to employees in form of training, which can vary depending of the depth, frequency, and level of detailed of the task that need to be learned. Edgar Dale developed the model "Cone of Experience", which refers to the different levels of abstraction to concrete experiences [58]. The model is explained with a pyramid, showing in the top of the pyramid, the lowest level of abstraction: words. Conversely, the bottom of the pyramid is showing the higher level of abstraction: real life experiences [58]. Based on this model a whole new theory was developed in order to explain the levels of retention with respect on the learning method that is applied. Consequently, the pyramid was adapted and percentages were incorporated to show the amount of knowledge that can be retained by an individuals depending on how this information is presented [59]. Some researches claim that this new "learning pyramid" lacks of evidence and proper validation with respect of the percentages that are shown [58]. However, the learning pyramid can be seen as a guideline in order to understand the different levels of retention, instead of a quantitated fact of individual retention. This means, that teachers and organizations can guide their methods considering this approach. But, they have also take into account the required background to perform each method, the expected outcome, and the limitations of the target that is going to be taught. Figure 4. presents the different average rates of retention developed by the National Training Laboratory [60]. The pyramid can be divided into two levels: passive and participatory teaching methods. Passive teaching methods refers to the different techniques in which the individual is not participating or is not playing an active role during the session, such as lectures, reading, audio-visual, and demonstrations. Conversely, participatory teaching methods refers to the techniques in which the individual plays an active role and is involved during the session, such as group discussions, practices, and teaching others [60]. Similarly, passive and participatory concepts can be described as cognitive and behavioral methods respectively.

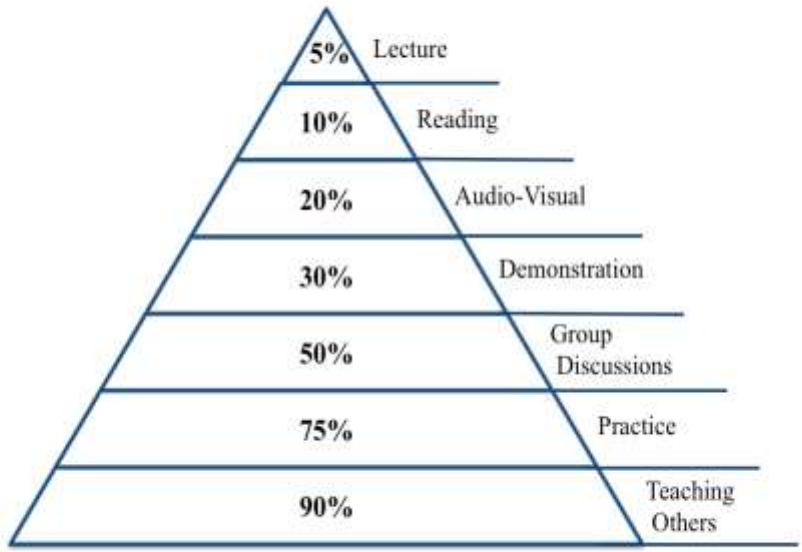

Figure 4 Training methods, adapted from [27]

Based on the pyramid, people can conclude that learning should be focusing just in the bottom of the pyramid and forget the traditional ways of learning such as lectures and reading. However, each method offers specific benefits that cannot be achieved only by focusing on the bottom of the pyramid. Thus, organizations have to provide training using a combination of two or more methods, in order to ensure that the knowledge is transferred. Likewise, organizations have to balance the cost-benefit associated with each technique and the appropriate scenarios to use them.

The cognitive approach is associated with transformation or addition of knowledge, by generating relationships among the existing and new knowledge [61]. Therefore, these types of techniques are focusing in teaching the rules of how to do something and providing the basic concepts and theories behind that [62]. In contrast, the behavioral approach is associated with skill development (learn by doing) and a change in behavior [61]. This type of technique focuses on providing practical training and allows participants to behave and think how they would act in real life. Generally, training objectives intend to achieve learning in knowledge, skills and attitudes. None of those techniques can achieve all three objectives at the same time. For that reason, training has to combine more than one method to perform a successful training program [63].

The advantages and disadvantages of each method of the learning pyramid are described below:

- *Lecture method:* is designed to develop an understating about a specific topic. The objective is to enhance theoretical knowledge through oral presentation. The interaction between trainer and trainee is limited to the questions and answers that can be raised during the presentation. Commonly, a lecture consists of an introduction, body of the lecture, conclusions, and a summary. This type of method is useful when you need to reach a large number of people. Moreover, lectures are less expensive than others techniques and serves as a basis for other techniques [63]. However, trainer should take into account the right balance between the amount of material to be taught and the period of time they have, due to the decreased effectiveness in retention [64].
- *Reading method:* is designed as a self-study technique, which basically, has the same objectives as lecture method, but there is no interaction between trainer and trainee. This type of technique allows trainees go back and check the material as

many times as they need [65]. Commonly, reading method is used in organizations to disseminate general knowledge regarding a specific topic, such as lessons learned and best practices.

- *Audio-visual method:* is designed to give trainees training through audio and visual at the same time. Therefore, trainees can be more focused in what is being taught [65]. This type of technique allows reaching large amount of people at the same time. Moreover, audio-visual methods allow participants to learn by watching how to do certain task and therefore, try to imitate what they see. Audio-visual techniques such as videos are widely used in organizations to show past incidents and their lessons learned. Videos have shown to improve quality of training because of the advantages that they offered, such as flexibility in the speed they want to learn, they can see events that are not easy to demonstrate, gives them consistent instructions about the topic, and an objective feedback [63].
- *Demonstration method:* is designed to show how to do something in order to teach skills. The demonstration technique allows trainers to show the step-by-step of a job task and the importance of each step involved in the process [63]. Moreover, demonstrations are useful to make the training more meaningful and realistic. Commonly, demonstration technique consists of a description of the main objectives, practical demonstration, summary of the key learning points, and in some cases the trainer allows the trainees to perform the same task, followed by questions and discussion [66]. This type of method is usually applied to teach how to follow a specific procedure [63].

- *Group discussion:* is designed to allow trainees to share their opinions and experiences about a certain topic. The objective of this technique is to improve analytical skills, logical reasoning, and problem solving. Additionally, it helps trainees to improve communications skills. Some of the most common types of group discussion methods are case study and role-play [66]. Case study is designed to apply theoretical concepts in applied context. The main objective is to give trainees a detailed description of a situation, where an organization deals with a difficult situation, and they have to analyze and identify the main causes of the event and suggest recommendations. This type of technique aims to improve analysis, synthesis and evaluation skills [63]. Similarly, in the role-play technique, trainees have to perform a character for a specific situation that recreates real life. The objective is to compare the performance with real life conditions and improve problem solving skills and the identification of them [66].
- *Practice:* refers to the type of training in which the trainee has the opportunity to get fully involved in the activity that is being taught. Thus, the trainees are expected to carry out the activity and demonstrate that they are able to do it correctly. Usually, a complete training program ends with some practical training in which the trainee is expected to develop specific skills regarding a specific job. Moreover, the trainee is able to experience how the learned skills and behaviors are transferred to the job, and how to deal with daily issues that arise during the job [63]. Some of the most common techniques for practical training are Job Instructional Technique (JIT) and simulators. Job instructional technique consists

of an explanation of the task, instructional plan, a demonstration, try out, and follow up. In this method, the trainee has to be able to explain how to perform the task before the execution of it. Similarly, simulators are used to imitate real life situations. This type of technique is widely used in the military and aerospace industry.

- *Teaching others:* the ultimate level of retention refers to teaching others, which refers to level of understanding that you have to achieved in order to be able to teach others. Once internalize a concept, they should be able to explain it to someone else.

2.6. Factors that influence learning

The learning process can be affected for several factors that can lead to unsuccessful learning outcomes. Those factors can be represented as physical and mental process that occurred in an individual level at the same time they are getting trained. Likewise, the different strategies implemented to transfer knowledge and the level of understanding of the target can also influence learning.

First, a well-established training program has to take into account the characteristics of the "adult learning" and the appropriate approach to reach them. Thus, the training program should considers the following aspects:

- Trainees need to know why they should learn: they have to understand the objective and why that is important [61].

- Meaningful training: they are more willing to learn when the information is linked to their job experiences [61].
- Opportunities to practice: they need spaces to rehearse and show the learned capability [61].
- Commit training to memory: they need to move the information from the short-term memory to the long-term memory. That means they need to receive detail information and determine that it is important [61].
- Feedback: they need to receive feedback regarding how well they are meeting the objectives and how to fill the current gaps [61].
- Spacing: teaching in various sessions instead of teaching all the material in short period of time, will increase the long-term memory [67].
- Test: testing increases learning and helps trainees to increase their long-term memory [67].

Second, the age of the trainees has shown influence on the learning process as certain mental capacities decrease over time. However, ages come with experience. Thus, in some cases experience can compensate age. Third, the mental precondition that the trainee brings to the training. This refers to the motivation and basic skills of the trainee. Fourth, the perception that the trainee gets from the information that he is receiving. This refers to the ability to organize and processed the information. Fifth, the ability of the trainee to convey new information with the existing knowledge and uses the information to influence behaviors. Finally, the ability of the trainee to adapts the new knowledge to new situations [68-70].

3. INCIDENT INVESTIGATION

3.1. Introduction

Incident investigation is one of the most powerful practices to learn from experience within an organization. This process allows organizations to receive feedback about their behavior and operational practices, in order to identify flaws in the system and overcome the deficiencies to prevent similar incidents and avoid catastrophes. High hazardous industries, such as, nuclear and chemical industries are more vulnerable to experience “organizational accidents” as called by James Reason [71]. These types of incidents are a combination of multiple failures that take place in complex systems. Even if this type of incidents has very low probability of occurrence, once it happens it is often catastrophic with devastating consequences that can involve people, infrastructure, and environment [71]. Thus, organizations have to focus their attention on improving the incident investigation program to detect latent failures that can lead to this type of disasters and implement risk-reducing measures to prevent them.

Incident investigation is defined as the systematic approach for determining the causes of an incident and the corresponding recommendations that may prevent or mitigate future incidents [72]. Moreover, this process helps organizations to identify failures in the management system that can reduce the risk of having another incident with similar root causes at the same facility or other facilities within the organization [72].

The classical Accident Causation theory or "Swiss Cheese Model" developed by Reason in 1997 makes a clear representation of the dynamics and path for an incident to happen [71, 73]. The theory suggested how high-consequence incidents could occur once latent and active failures are aligned, as depicted graphically in Figure 5. Latent failures refer to deficiencies or flaws associated with organizational factors, supervision or preconditions for unsafe acts. While, active failures refer to unsafe acts that act as the triggering event [73, 74].

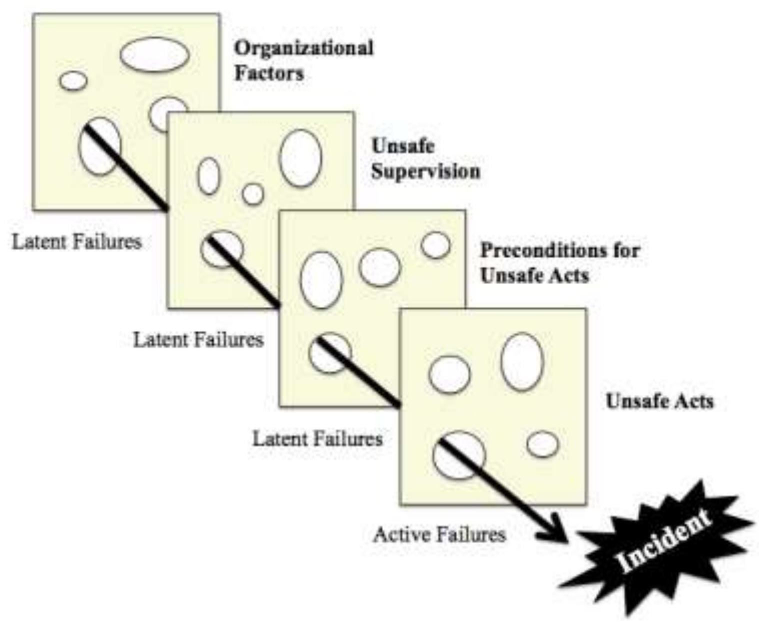

Figure 5 Swiss Cheese model, adapted from [71]

The interaction between latent and active failures that lead to a catastrophic incident is hard to detect and understand, due to the complexity and limited number of such incidents. Thus, learning from high consequences incidents limited the amount of knowledge that need to be learned and only shows partial reality of the organization. Research has shown that in order to unhide latent failures, it is necessary to investigate all type of incidents that have significance and therefore, help to prevent disasters [75].

Figure 6 Safety pyramid, adapted from [75]

H.W. Heinrich was the first person to introduce the safety pyramid in his book Industrial Accident Prevention in 1931. The safety pyramid refers to the ratio of the number of minor incidents and near misses that occur before a major incident takes place [76]. The pyramid has been validated and slightly modified by Frank E. Bird Jr. in 1996 and later on by ConocoPhillips Marine in 2003 [75]. The study made by ConocoPhillips Marine suggests that for one fatality incident, an organization has 30 severe incidents, 300 minor incidents, 3,000 near misses, and 300,000 at-risk behaviors or unsafe acts

[75]. As a result, organizations has to focus their attention to the bottom of the pyramid, where they can identify trends and find useful information to take the necessary preventive actions and improve safety management systems. Figure 6. Presents a graphic description of the safety pyramid.

3.2. Incident investigation terminology

The safety pyramid provides a general understanding of the different types of incidents that an organization can experience depending of the severity of them. There is not general agreement regarding incident classification. Even so, organizations recognize the importance of classifying the nature of the incident in order to determine the appropriate approach to investigate them [77]. Therefore, based on literature and previous experience, a general description and classification is provided below:

- Incident: a work-related unplanned event, which has or may have undesirable consequence, such as harm to people, damage infrastructure or the environment [72, 78]. The definition of incident and accident are commonly mixed and used for the same purpose. However, the definitions differ with respect of the capability to be prevented or not. In this sense, it implies that an incident could be prevented if something had been done differently.
- Catastrophic incident: work-related incident, which has major consequences usually involving fatalities, severe off-site environmental impact, and/or severe community impact [77]. Some examples of catastrophic incidents are Bhopal in 1984 and Macondo Blowout and explosion in 2010.

- Severe and minor incident: this type of classification varies depending on the risk matrix applied in the company. Usually, a severe incident involves major injuries, major interruptions to operation, and/or evacuation of personal. Conversely, minor incidents usually refer to incidents that have no major consequences to people, infrastructure or the environment.
- Near miss: in terms of process safety, near miss is defined by the Mary Kay O'Connor Process Safety Center as the event in which the loss of containment is prevented by the last layer of protection in the process [79]. Likewise, near misses refer to events with no undesirable consequences, but any changes in the circumstances could have produced actual consequences [80].

The terminology used in incident investigations has been challenging over the years because there is not a general understanding among the concepts and the methodologies applied by organizations. As a result, organizations fail to understand the difference among concepts such as root causes, contributing factors, and direct causes and the importance to recognized and identifies each of them in order to develop effective investigations and prevent incidents to happen again. For the purpose of this research those concepts are defined as follow:

- Causal factor: an event or condition necessary to produce or contribute to the incident [81], *i.e.*, that if eliminated would have prevented the incident or reduced the consequences of it [72]. Causal factors can be classified into root cause, contributing factor, and direct cause [81].
- Direct cause: refers to the immediate events that lead to the incident [82].

- Root cause: refers to the underlying causes and the most basic causes of an incident, that if removed, the incident would not have happened. Root causes are associated with failures in the management system, which can be categorized into failures in the system design or failures in system implementation [79].
- Contributing factor: "factors that facilitate the occurrence of an incident such as physical conditions and management practices" [72].

The level of detail of each incident investigation varies from company to company but it is usually associated with the severity of the incident. Thus, high potential incidents such as near misses with high significance could be excluded for detailed analysis and the company may lose valuable findings that can lead to the identification of failures in the management system. For that reason, companies should take into account variables such as the nature, complexity, and the actual or potential severity of the incident, in order to determine the appropriate team and the level of analysis required for each incident [77].

It should be noted that although not all incidents will be investigated in detail or investigated at all, they have to be reported and recorded in an internal database to identify trends and keep track of all incidents within the organization. In this context, organizations should investigate the following incidents [79]:

- Catastrophic and major incidents.
- Minor incidents with significance, *i.e.*, incidents with high potential consequences.
- Near misses with significance, *i.e.*, incidents in which the outcome could have been serious if the circumstances were slightly different [79].

- Minor recurring incidents or recurring near misses identified by trend analysis.

3.3. Incident investigation history

Although, incident investigation theory has been changing over the years and new methodologies have been developed to address the complexity of new systems and technologies in the industry. Incident investigation still conserves most of the basis and assumptions developed in the earliest accident causation theories. Herbert W. Heinrich is considered the pioneered of accident causation theory, introducing the domino theory of accident causation back in 1931 [82]. The domino theory described the occurrence of an incident based on the culmination of a series of events, which occur in a logical sequence. Thus, an incident (called by the author as accident) can be prevented if the series of events are disturbed [84]. The events are defined as dominos and are classified into five categories: social environment and ancestry, fault of the person, unsafe act or condition, incident, and injury. The theory is lined with the assumptions of incidents prevention: focusing in people, which are responsible of the incidents and management, where the incident can be prevented [82]. Moreover, Heinrich developed and set the basis of the safety pyramid and created a general understanding about the importance of accident theory.

The work done by Herbert W. Heinrich sets the starting point for the accident causation theory, which over the years has evolved based on the level of complexity that arises for an incident to occur. In this sense, the accident causation field has been divided into three main ways of thinking. These three categories are: simple linear or sequential model, complex linear or epidemiological model, and complex nonlinear model. Those types of theories have been focused in the identification of single causes, multiple causes, and complex outcomes, respectively [83]. It should be noted that the combination of those theories and level of understanding of each way of thinking have shaped our current understanding about incident investigation and risk analysis.

Simple linear model refers to Heinrich domino accident causation theory explained previously, in which an accident can be prevented by eliminating or disturbing one of the factors or dominos [83]. Similarly, Bird and Germain developed the Loss Causation Model in 1985, in which a modified domino theory was established by the incorporation of management factors in order to explain their relationship with the causes and consequences of an incident [84].

Conversely, complex linear models focused in the identification and elimination of root causes and the identification of the required barriers or controls in order to prevent incidents. Moreover, these theories incorporated the interactions between the individual and the system leading to unsafe conditions. Complex linear models can be explained by a combination of theories such as energy damage theory, time sequence model, epidemiological model, and systemic theories [85]. Complex linear theory is highly recognized by the work done by James Reason [74] and Jens Rasmussen [57, 86], which have had a significant impact in accident causation theory. Those theories are based on a system-oriented approach and were able to change the perspective from the traditional human error approach to a systematic organizational approach [84].

Finally, complex non-linear models refer to the new tendency of thinking, in which the non-linear incident causation is recognized. Thus, incidents are the result of a combination of mutually interacting variables involved in complex environments. This generation of thinking highlights the research done by Hollnagel and Leveson. Both of them are recognized by the development of non-linear accident models in the 2000s [78]. The models are: The Systems-Theoretic Accident Model and Process (STAMP) developed by Leveson and The Functional Resonance Accident Model (FRAM) developed by Hollnagel [83]. STAMP model considers systems in dynamic equilibrium and analyzes the dysfunctional interactions among components that are part of the system. Moreover, the model classified the different types of flaws that can lead to an incident and analyzes the role of constraints in safety management systems [87]. Alternatively, FRAM model considers that system alterations lead to incidents when the system cannot hold up such alterations. Thus, the model identified the different variables within an organization and how to manage those alterations that can arise in order to produce an incident [88].

These three generations of thinking, overlap over the years and combine theories and models in order to suggest better approaches to understand real systems behaviors [83]. Meanwhile, a considerable amount of methods have been developed for incident investigation and those methods have been focused in the identification of root causes. An older methodology, The Management Oversight and risk Tree – MORT, developed by Johnson in 1973, provides a detail and comprehensive understanding for root causes identification [89]. However, their application has been limited due to their complexity and the required time to executed it. Even so, later methodologies have been developed based on MORT methodology. Nowadays, organizations have spent significant amount of resources in the development of computerized methodologies, which reduces time and helps standardizing the process [90].

3.4. Incident investigation team

The incident investigation team is a critical element for the development of successful incident investigations processes, because their expertise and teamwork will shape the quality of the recommendations and the degree of analysis of the identified causes. Usually, the top management along with the safety department are in charge of selecting the incident investigation team based on the severity and the nature of the incident [80]. The team is selected based on their experience, skills, and competencies associated to the process, where the incident occurred, as well as, the competencies and skills related with incident investigation methodologies. Since organizations usually are in charge of multiple types of processes and products, it is not practical to have only one team trained to perform incident investigations. Thus, organizations should have a pool of trained employees across the company, who will be familiar with incident investigation process and the methodologies that need to be applied [77]. The team composition will vary depending of the specific required knowledge for the investigation. Generally, an investigation team is composed but not limit to [77, 79, 80]:

- Leader trained in incident investigations
- Process operators, who will bring expertise of the process where the event happened

- Process engineers and process safety specialists
- Maintenance and technical specialists
- Contractors representatives
- Law representatives
- Potential involvement of third parties depending of the nature of the incident.

In order to bring the objectivity to the investigation, it is a common practice to involve employees from sister units or plants, who are familiar with the process and can provide the necessary technical expertise in the investigation. Likewise, it is also a common practice to include someone, who can help during the investigation with specific technical inquiries [80]. Furthermore, some organizations try to avoid including managers or people from the top level management to the team, because it can inhibit an open communication within the members of the team [77]. Finally, it is also a common practice to provide training to the team prior the investigation to provide an appropriate background about the incident, required personal protective equipment, emergency response, and incident investigation methodology that is going to be applied [80].

It should be noticed that the responsibilities assigned to the team are temporary and required their full time in order to gather and analyze the information. Therefore, it is important that managers understand their role and the temporary suspension of their routine responsibilities [77, 80].

After the team has been selected the team members will have to go through the whole incident investigation process, since gathering the information until the development of the recommendations. One of the most challenging steps is the identification and collection of evidence. Since, evidences can be easily disturbed and manipulated by external sources. Moreover, based on the nature of the incident, there may be more than one team investigating the incident, making even harder to perform the job. Thus, the team has to act fast but at the same time be careful identifying potential hazards to the team, trying to look the big picture of the scene, noting what is missing and what is there that should not be there, and using all senses to get as much evidence as possible. At the same time, they have to develop a list of preliminary potential scenarios, which are going to be the main source for identifying the required evidence and factors that contribute to the incident [80].

3.5 Incident investigation process

Once an incident occurs, the incident must be reported and classified accordingly, in order to arrange the required resources and determine the best strategies to approach the following investigation. This section addresses the different phases or steps required to perform incident investigations, since the reporting of the incident until developing and implementation of the recommendations [91].

To ensure a successful incident investigation, organizations have to ensure that a proper incident investigation management system has been developed and implemented. The incident investigation management system sets the basis and criteria of how an incident is going to be handled and the procedures that need to be followed during this process [72]. A common management system needs to consider at least but no limited to the following elements [72, 85]:

- Organization’s responsibilities
- Roles, relationships, and communication with others teams and departments
- Regulatory issues and their role
- Incident classification criteria
- Team composition
- Required documentation
- Incident investigation methodologies
- Required training
- Reports
- Resources
- Incident investigation procedures
- Interview forms

3.5.1. Reporting

The incident investigation management system should encourage and create a reporting culture, where the employees feel confidents to report unsafe behaviors, near misses and minor incidents. Likewise, a culture of no blame will allow employees to talk and report without fear of potential consequences. Reporting must be made as quickly as possible, in order to provide immediate response and preserve the evidence without external alterations. There are two types of reporting to be taken into account once the incident occurred. The first one is the internal reporting, which refers to reporting from employees to the incident investigation management system and also the corresponding report within the organization, to alert the departments and people that need to be informed about the event. This type of reporting can be via paper, online or verbal. The second type of reporting, depends of the severity of the incident, in which external entities such as regulators and firefighters must be informed about the incident [91].

After the incident has been reported, the next step is to classify it, record it, and determine how it is going to be approached. Then, the incident investigation team must be selected to execute the investigation.

3.5.2. Collecting evidence

Gathering evidence is one of the most challenging and time consuming stages during incident investigations, because in some cases, evidence is damaged, documentation is not available or it is difficult to access, and witnesses may have conflicting versions of what happened. Therefore, preserving and verifying evidence requires experience and a rigorous plan that must be followed [81]. In this step, it is important that prior to start collecting data, the team leader and team members available at that time, develop a plan, which will guide the evidence collection. It is likely that the plan is going to change as the investigation progresses [72].

The evidence or data can be classified into three types: human, physical or documentary. Human evidence refers to witness statements or interviews, as well as observations. Physical evidence refers to any physical source relevant to the incident such as equipment, mechanical parts or chemicals. Documentary evidence refers to the paper and electronic documentation, such as procedures, logs and reports [81].

Besides the information that can be collected inside the organization, there may be additional sources that will support the investigation. Some of these of sources are:

equipment manufacturers, universities research centers, external databases, government records, and companies with similar processes. As a result, not all evidence is collected during the site visit, there may be data or information that will result from additional analysis such as laboratory experiments, testing or external interviews [72].

The severity of the incident will determine how easily and quickly the incident investigation team will have access to the evidence. In the case of major process safety incidents, there may be external entities in place such as OSHA, EPA or insurance companies that will limit the access to the site and the availability of information. At the same time, the physical damaged of the site can affect the collection of data, and most of the witness will be unavailable at the moment [72].

3.5.3. Analyzing the evidence

An objective investigation must consider all realistic scenarios that possibly lead to an incident. Then, based on the collected evidence, each scenario will be tested and consequently will be rejected or accepted. All scenarios must be documented and reevaluated accordingly if new evidence is gathered [80]. The objective of this stage is to identify the direct causes, root causes, and contributing factors in the incident, in order to be able to answer the questions of what happened and why did it happen [81]. As established in the incident investigation management system, a predefined methodology is going to be applied to identify the root causes of the incident. Generally, root cause methodologies start by identifying a timeline or sequence diagram, which set a basic understanding of the incident, main events, and conditions [72]. The next steps vary depending of the methodology that is going to be used. Some of the most relevant methodologies for analysis of evidence and identification of root causes are further discussed in next section.

3.5.4. Developing recommendations

The final outcome of incident investigations is the recommendation that are generated based on the root causes and contributing factors identified through the investigation. During this process, each cause has to be analyzed individually and a proposed action or recommendation should arise from this analysis. The recommendations have to be clearly defined, measurable and feasible. Likewise, the objective and risk reduction action should be easily understood. Since the recommendations will impact the management system of the organization, it is important that recommendations go through a management of change evaluation before they are approved [72]. Moreover, it is also a common practice that the recommendations are risk-ranked to determine priority for implementation along with a cost-benefit analysis in order to determine the feasibility of the recommendations. All recommendations need to be evaluated and approved by the management and depending of the nature of the incident, the legal department may need to review and approve the recommendations as well. Once the recommendations are approved, the people in charge of the execution of each recommendation are assigned and a timeline is defined. Finally, the management system is responsible for tracking the implementation status of those recommendations as well as document the resolution of each recommendation. Only until the recommendations are implemented, organizations are reducing the risk and consequently learning from incidents [80].

3.5.5. Report and lessons learned

The final stage of the incident investigation process involved the development of a written report, which contains all documentation involved during the process. The report covers all the detailed information used during the investigation, since evidence, causes until recommendations. Generally, an incident report format includes at least the following elements: summary, background, description of the incident, root causes, recommendations, and appendix. Finally, the lessons learned are expected to be communicated with all interested parties in order to ensured learning across the industry [80].

3.6 Incident investigation methodologies

3.6.1. Fault tree analysis

Fault tree analysis is a graphic methodology, whose objective is to identify "why" an incident happened [72]. The methodology uses logical reasoning to determine the possible combinations or pathways that lead to an incident. Those combinations can be associated with equipment or component failures, human factors, or organizational factors [92]. Fault tree analysis uses starting point as the top event, which refers to the outcome of the incident. Then, the process consists of going backwards in order to identify the preceding causes or events, until the root causes are finally identified. The level of detail of this technique will depend of the incident investigation team. A FTA can be used as a qualitative method, quantitative method or both [81]. The methodology uses symbols to guide readers to understand the different pathways and logic of the diagram. Figure 7. Present the most relevant symbols for developing fault trees.

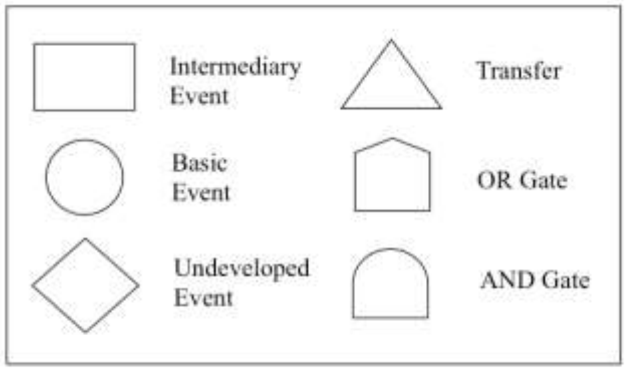

Figure 7 FTA symbols, adapted from [77]

The symbols AND and OR represent the gates that connect one event to one or multiple events. The gate AND indicates that the outcome event occurs only if all the input events occur. Conversely, the gate OR indicates that one or more input events have to occur to produce the outcome event [72]. Figure 8. shows a basic representation of a FTA.

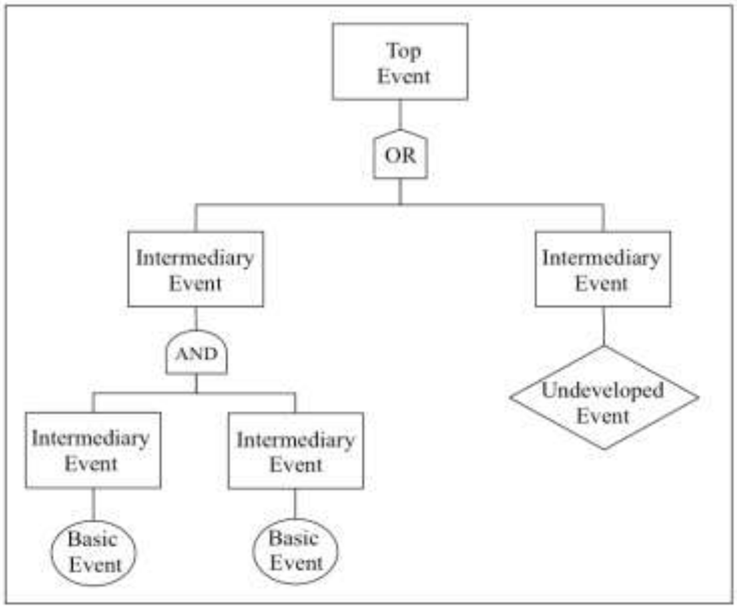

Figure 8 Basic representation of a FTA, adapted from [81]

3.6.2. STEP (Sequential Timed Events Plotting)

Sequential timed events plotting is a systematic methodology for incident investigation (accident investigation as called by the author) developed by Hendrick and Benner (1987) [93]. STEP is a multi-linear event sequence, which provides a detailed description of the incident process. The methodology focuses in the identification of the authors and the sequence of events or actions that lead to the incident. Thus, STEP considers that multiple actions can take place at the same time by different authors. The authors are considered as people or things directly involved in the incident [93].

The incident need to be analyzed looking for the big picture and then breaking down into actors and actions. In order to accomplish that Hendrick ad Benner introduced the term "making mental movies", which refers to the visualization of each action executed by each actor from the time the incident was expected to began, until the top event of the incident. The methodology process is supported by a STEP worksheet, which helps to visualize and link all the events together. The STEP worksheet is described as a matrix, in which the authors are identified in the rows and the events in the columns, as shown in Figure 9. To ensure logical sequence, the events are linked by arrows that represent the flow of the incident [93].

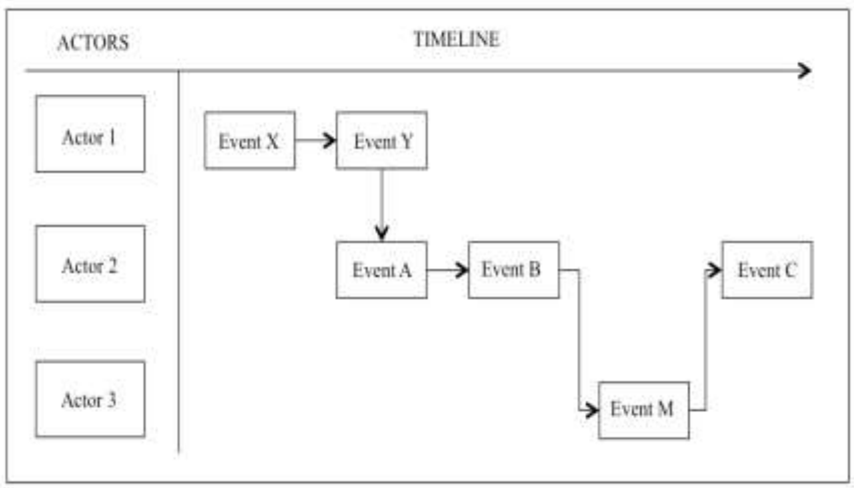

Figure 9 Basic STEP diagram, adapted from [93]

After the diagram is completed, the incident investigation result is subject to three different types of tests: row test, column test, and necessary and sufficient test. The row test verifies that the actions and authors are broken down sufficiently. The column test verifies that the sequence of events is consistent and coherent. Finally, the necessary and sufficient test verifies that the previous event is sufficient to produce the outcome event [82]. The STEP worksheet is then analyzed in order to identify the event or events that generate safety problems. Each safety problem is then analyzed as candidate for recommendation [82].

3.6.3. FRAM (Functional Resonance Analysis Method)

Functional resonance analysis method provides a socio-technical approach in order to analyze and understand the functions of the system. The objective of the method is to determine what should have happened that did not happen. To do that, FRAM analyzes the potential variability and functional resonance in the system [94]. FRAM is based on the development of four steps:

First, the identification of daily functions required in the system. Functions refer to the activities required to produce a specific outcome. Thus, the first step required to determine all possible functions involved in the system as well as the identification of the attributes of each function. The attributes refer to the characterization of the functions, which are described into six aspects as shown in Figure 10 [94].

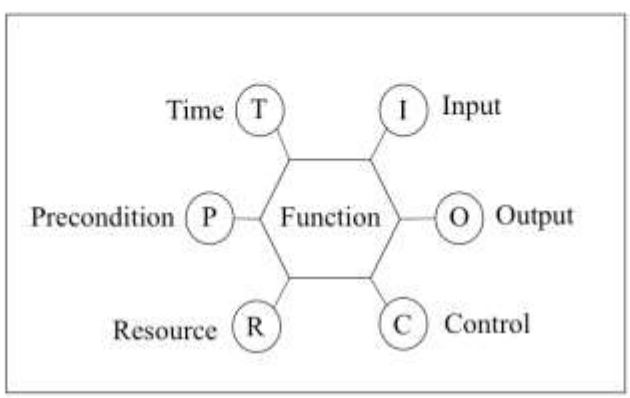

Figure 10 FRAM Function diagram, adapted from [94]

Second, the characterization of the variability of each function. This characterization is based on eleven Common Performance Conditions (CPCs). Those elements take into account human, technological, and organizational factors. The variability is determined considering both the potential and actual variability of the system [94]. Third, the identification of coupling functions and their interrelation in order to identify unexpected outcomes. This step requires to link all the identified functions and understand the potential variability that can be expected from that. Finally, the last step refers to the identification of barriers for variability and performance monitoring. Barriers can be divided into system and function barriers. System barriers refer to organizational aspects and physical barriers. Conversely, functions barriers refer to the way barriers can achieved their purpose. At the end, recommendations are going to be develop to enhance the identified barriers [94].

3.6.4. Tripod BETA

Tripod Beta is a systematic method to perform incident investigations. The method is based on the accident causation theory or Swiss Cheese Model. This methodology was formalized by Shell International and provides an understanding of the influences of human behavior and organizational factors in the system. Tripod theory focuses in the identification of environment conditions (organizational factors) in which humans work, rather than human conditions that lead to the incident. Thus, the ultimate goal is the identification of failures in the management system and organizational culture. Likewise, the methodology provides three main objectives: development of the chain of events that lead to the incident, identification of the barriers that should have prevented the incident, and the identification of the underling or root causes [95].

The first step, is the development of a “core diagram”, which refers to the graphical representation of the events. The core diagram is developed based on the identification of Tripod Beta trios: Agent, object, and the event. Then, the trios are connected among them to provide a chain and sequence of events. The second step refers to the identification of the immediate causes that allowed barrier failing. The third step refers to the detailed understanding of why it happened. Thus, the preconditions and underling causes of the incident are identified. Finally, the previous steps are repeated until all the evidence is collected and analyzed [95].

In addition, Tripod Beta defined eleven mechanisms or Basic Risk Factors (BRFs) to categorize and guide the identification of underlying causes. Those BRFs are: design, tools and equipment, maintenance, housekeeping, error enforcing conditions, procedures, training, communication, incompatible goals, organizations, and defenses [82].

3.6.5. IPICA (Integrated Procedure of Incident Cause Analysis)

Integrated procedure of incident analysis is a method for incident investigation based on the traditional Root Cause Analysis (RCA) method. The RCA is a complex linear method, whose goal is the identification of casual factors and root causes of an incident. The method mainly involved the following steps: development of incident sequence, identification of causal factors, development of causal factor chart, and the identification of root causes. The last step can be achieved by two different approaches:

using logic trees or using predefined trees. IPICA follows the second approach using predefined trees [96].

IPICA suggests an innovative approach, which addressed the limitations of RCA method identified by the author. The methodology is focused in the improvement on three main areas: assumptions of the nature of incident causes, limited definition of root causes and the methods applied for their identification and the complex non-linear effect in incidents. IPICA identifies four incident cause levels: implementation, organizational, management's attitudes, and societal. The first level is considered as the direct causes of the incident, which are associated with the meta-components, *i.e.,* interaction of hardware, software and personnel. The second level identifies failures in the management system and safety culture of the organization. In order to identify this, a root cause map is developed based on the CCPS guidelines to construct process safety management systems [72]. The third and fourth levels are required when the causal factors are associated with factors beyond the organizational boundaries. To identify those factors, the implementation of non-linear techniques such as STAMP or safety archetypes is needed [96].

3.6.6. TapRooT® System

TapRooT® System combines a process and set of tools to investigate incidents and develop corrective actions. The system goes beyond the identification of the causes of the problem, instead the system supports investigators through the whole incident investigation process, since the collection of data, until the presentation of results and recommendations to the top management level and interested parties. TapRooT® is a software, which uses and combines multiple techniques in order to achieve detailed and improved results [97].

The system consists in the execution of seven steps. The first step refers to the collection of the required information. The second step is the development of a sequence of events. In the third step the causal factors are identified. The second and third steps are supported by techniques such as SnapCharT® and Equifactor®. The fourth step refers to the identification of root causes, in which tools such as Root Cause Tree® and dictionary are used to help investigators in the identification of all the root causes. The root cause tree is divided into seven main categories and it is then break down into more detailed. The seven categories are: procedures, communication, work direction, training, management system, quality control, and human engineering. In addition, the root cause tree includes a set of fifteen questions to help investigators analyze human factors in more detail. Once the main root causes have been identified, the system guides the investigator in the identification of more complex causes such as culture, systemic, and organizational factors. The following steps refer to the analyzes of the root causes, development of recommendations, reporting and implementation those recommendations [98].

3.6.7. MORT (Management Oversight and Risk Tree)

Management Oversight and Risk Tree is an incident investigation methodology developed by William Johnson. MORT consists of a predefined tree based on fault tree analysis methodology. The main objective of the methodology is to go through each branch in the tree and analyzes whether or not the associated causes are applicable to the event. The branches end with the identification of failures in the management system [92]. Thus, the methodology uses a schematic representation of a dynamic and ideal management system model [89].

The logic diagram identifies 98 generic problems and over 1500 basic causes or root causes associated with failures in the management system. The diagram starts with the top event followed by an OR gate, which derived the first important analyses that need to be done. The OR gate breaks down into two main branches: Management oversight and omissions or assumed risk. Assumed risk refers to the risks that have been analyzed and accepted by the management level. Conversely, unknown and unanalyzed risks are considered in management oversight and omissions. The next step requires to answer the questions 'why' and 'what happened'. The 'why' refers to the management system factors, while the 'what happened' refers to the specific controls that should be in place [99].

In order to perform the analyses, the diagram is supported with a manual that helps investigators to ask the right questions in each level of the analysis. Likewise, the methodology uses a color-coding system to help investigators visualize the progress and identify the areas that need additional information or analysis. The events that are not applicable to the incident should be colored in black. For the remaining events, a comprehensive evaluation needs to be done to understand if the event was adequate or not. If the event is considered Less Than Adequate (LTA), it should be colored in red. On the contrary, if the event is considered adequate, it is colored with green. In some cases, events can not be classified into those two categories because of lack of information or uncertainty about this specific event. Those events are colored in blue and needs to be evaluated in more detail or more data need to be collected. The MORT analysis finished when all the blue events has been evaluated and consequently decided whether it is considered LTA or adequate [89, 99].

3.6.8. STAMP (Systems-Theoretic Accident Model and Processes)

Systems-Theoretic Accident Model and Processes is an accident model based on system theory, developed by Nancy Leveson. STAMP describes accidents as inadequate control or enforcement of safety constraints in the system, instead of components failures. Thus, STAMP focuses in understanding why the control structure was inadequate and which feedback loops failed in the system. Likewise, STAMP considers safety as part of an adaptive socio-technical system, in which all the components are interrelated and are kept in a dynamic equilibrium [87].

STAMP is based in the understanding and analysis of three basic concepts: constrains, control loops and process models, and levels of control. These concepts contextualize a classification of control flaws that help investigators to identify all factors involved in the incident [100]. First, accidents are conceived as the identification of constrains rather than events. Thus, STAMP identifies all the required constrains in the system, including the social and organizational factors and no just system design constraints. In addition, systems are conceived as hierarchical structures, in which each level imposes constraints to the lower level in order to control the system. In this sense, safety has two basic hierarchical levels of control: system development and system operation. Those levels of control must interact and develop effective channels of communication. Each level in the control structure must define the different channels of enforcement and communication. Thus, each hierarchical level will impose constraints downward and will receive feedback upward to verify the effectiveness of those constraints. Finally, the concept of control loops and process models refers to the consistency that must be achieved between the model of the process used by the controllers (human or automated) and the actual process state. In this sense, the controllers are able to supervise the actual state of the system [87].

STAMP developed a classification of flaws in the components of the system development and operations to support investigators in the analyses process. The classification is divided into three main branches: inadequate enforcement of constrains, inadequate execution of constrains and inadequate feedback. Each branch is then divided in more detail to identify al the factors involved in the incident [87].

3.7. Developing quality incident investigation reports

In incident investigations, all the effort and resources spent on it are going to shape the quality of the final product of the process: the incident investigation report. Therefore, identifying real root causes, developing quality recommendations, and making sure the recommendations are implemented are key elements to success in this process and reducing the risk in order to prevent similar incidents in the future. The incident investigation process allows organizations to analyze their system behavior and uncover hidden organizational, cultural, and technical flaws that are not visible in their day-to-day work. The process has to be performed with rigorousness, time, and making sure the organization understands the importance and valuable output they can get from it. Otherwise, the process is going to be seen as a useless secondary work that needs to be done to comply. Having a good incident report and an overall good incident investigation program enables organizations to continually improve and over time ensuring a reliable process safety management system and high standard operational processes. In this sense, learning from incidents allows organizations to improve, be more competitive, and safe money. As Klezt stated, if organizations think safety is expensive, try an accident [14].

Quality incident investigation reports are the based on recommendations that are clearly defined and are intended to solve the identified causes on a feasible and measurable way. This means, that the documentation and analysis are not going to be limited to generating information, but also to making sure that knowledge is created upon that. Similarly, it is important to make sure that the created knowledge becomes part of their management systems and operations. Once the organization creates and accumulates knowledge within it, the next step is to collectively acquire and implement this knowledge across the organization and industry, to make sure no one is doomed to make the same mistakes. This can only be achieved by sharing the lessons learned and ensuring those lessons are not forgotten. Trevor argued that achieving the first step (spreading the message) is relatively easy. However, ensuring that this message would become part of the organization is the real challenge [14]. Likewise, he asserted that "organizations have no memory, only people have memories and they move on" [14].

Therefore, it is important to share lessons learned, create knowledge and make sure it will not remain just on paper.

4. LEARNING PROCESS

Learning can be defined as the process in which humans acquire or modify knowledge through experience, education, or training [101]. Humans have the ability to learn and this process is based on their previous knowledge. Thus, the results from the same experience or training can be different for each person. Moreover, learning is not a linear process. It follows a learning curve, which decreases over time if not adequate reinforcement is performed. In order to ensure that learning has been achieved, a modification of human mental models and/or changes in their routine behavior is expected.

When it comes to learning inside an organization, human behavior cannot be considered as a single component in the organizational system. It is required to consider the interactions and relationships among them. Thus, the learning process is no longer considered as an individual process, instead, it is considered as an organizational process, in which, people try to acquire knowledge together and preserve it over time. The challenge is to ensure that everyone within the organization manages, interprets, and transfers knowledge effectively as needed. Likewise, companies have to ensure that knowledge will remain available even if there are changes in personnel. As stated by Kletz, "organizations have no memory, only people have memory and they move on" [15]. In this context, organizations have been focusing on how to manage knowledge and preserve it over time. These with the purpose of improve continually, avoid the same mistakes, and consequently prevent incidents.

4.1. Learning system

In the learning system for the chemical and oil and gas industry, three entities can be identified as components that have the ability to learn: individual, organization, and industry. For the purpose of this research, the learning is based on previous incidents, the implementation of lessons learned, and best practices. Learning occurs from the smallest entity to the biggest one. Thus, once an incident occurs, the individuals involved in it are going to challenge their mental models and identify the potential causes of the incident and consequently learn from experience. However, due to the complexity of the human behavior, it can be expected that a small portion of the people who experience an incident, choose to ignore it.

Depending on the severity of the incident, reporting plays an important role in the learning system. In the case of near misses, the safety culture of the organization is challenged and the individuals involved in the near miss have to decide whether or not to report the event. On the contrary, in the case of a major incident, the process safety team is usually part of the immediate executive actions; therefore, reporting is not required from the individuals that experienced the incidents to the safety team. Moreover, organizations need to notify the corresponding regulatory agencies and determine their role in the investigation process.

Once the incident is reported, the significance of the incident needs to be determined. In this process, the safety team has to evaluate the impact of the incident and based on those results, the safety team would determine whether or not the incident would be investigated in detail. This means to perform an incident investigation process, in which the root causes, lessons learned, and recommendations are determined. Organizational learning occurs once each individual who is part of the organization has acquired and processed the new knowledge that is being taught and collectively implement the lessons learned. The ultimate level of learning is the industry learning, in which the organizations share the lessons learned and transfer the existing knowledge across the industry. This is done with the objective of having an updated knowledge and improves collectively. Figure 11. shows the system explained before.

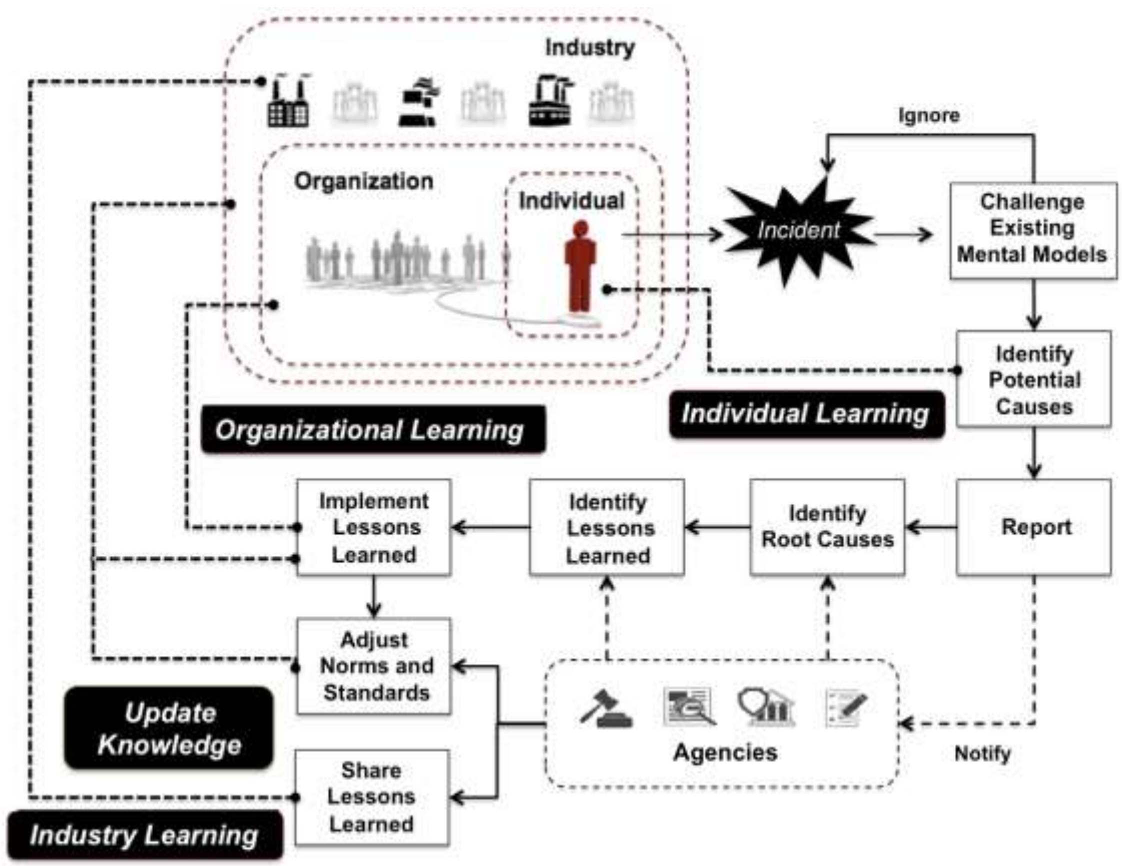

Figure 11 Learning system, adapted from [90]

4.1.1. Limitations in the learning system

The learning system presented in the previous section, gives an idea of how the system works, the entities involved and their role in the learning process. Additionally, it gives a bigger picture of the main steps and sequence of the learning process. Based on this diagram, together with the available literature review in this field, it is evident that organizations still see knowledge as temporal factor that is inherent to the people involved in the organization, instead of a part of their management systems. Thus, organizations fail to transcend from individual learning to organizational learning. In addition, they fail to provide the required tools to enhance the individual learning process in order to ensure higher levels of retention and sense of ownership. Finally, the chemical and oil and gas industry fails to understand the need of putting all resources together to improve as a whole. In this context, several limitations that inhibit learning have been identified:

- *Identification of root causes:* the incident investigation management systems set the basis to ensure learning from incidents, because it ensures that the fundamental causes of the incidents have been identified and managed properly. Thus, incident investigation requires an appropriate level of expertise during all phases of investigation, from the collection of evidence until the development of recommendations. This would ensure that the collected data is reliable, adequate, and complete. Moreover, that the analysis has been performed with sufficient detail and the root causes have been identified. Organizations tend to identify direct causes as the root causes of incidents. Thus, recommendations tend to solve superficial problems that do not prevent similar incidents in the future. Direct causes such as human error are usually identified as root cause, and investigation process ends placing the blame on the operators instead of identifying failures in the management system that contributed to the execution of the unsafe acts. This misinterpretation of concepts inhibits organizations from developing high quality incident reports and blocks the continuous improvement of the management systems. Organizations need to ensure three key elements in order to be able to identify root causes. First, they have to provide adequate tools to perform the analysis of the investigation. The incident investigation team needs to be supported with standardized methodologies and procedures to guide them through the whole process. Second, organizations have to provide appropriate training regarding incident investigation to ensure a pool of trained people who are familiar with the incident investigation process and methodologies applied in the organization. Finally, organizations have to ensure appropriate level of expertise based on the nature of the incident to guarantee the required technical knowledge during the analysis.

- *Promote reporting of near misses*: learning should be promoted from every valuable source of information. Therefore, organizations do not have to wait until a major incident happened to improve their system. Acquiring data and information and analyzing it, give the opportunity to learn and consequently prevent the occurrence of major incidents and avoid losses. In this context, near misses give a significant amount of information to identify trends and high potential consequence incidents.

It can also helps identifying failures in the management system and consequently provide improvement opportunities. Promoting the report of near misses becomes a crucial element for organizations to analyze more frequent incidents and extract their knowledge. Achieving the expected results is challenging for organizations because it requires a healthy reporting culture, in which the individual punishment is avoided. This means, creating an open culture, where employees feel confident to report incidents and everyone feel responsible for their own and their co-workers safety. Moreover, promoting the report of near misses require the engagement of the top management level to ensure the required resources and time.

- *Ensure implementation of lessons learned:* Organizations usually spend a significant amount of resources during incident investigations processes. However, this effort decreases drastically once the recommendations have been developed and the final report has been presented. Organizations fail to support the implementation process and therefore, no actual learning is performed. In the majority of the cases, learning is limited to the development of the report but actions are not executed. Thus, organizations inhibit the organizational learning because no actual knowledge has been transfer to the organization. Moreover, investigators play an important role in the development of those recommendations, in order to ensure that they are clear, measurable, and feasible; and consequently, people in charge of executing those actions can easily understand what is intended and set the right timeline and resources.

- *Ensure sharing knowledge within the organization:* the ultimate goal of incident investigations is to prevent similar incidents from happening again. In this sense, the extracted learning from those investigations should to be spread out across the organization in order to ensure that different facilities all around the world, can get those lessons and extract their knowledge. Although organizations communicate lessons learned, they usually fail to give the message in an appropriate way. This means to understand the different types of targets across the organization and unpack those lessons learned in a way that people can understand how those lessons would impact them. Furthermore, this sharing is limited in most of the cases to safety moments or emails, but there is no discussion or analysis of the applicability of those lessons to their own process or facility.
- *Use and understanding of databases and academic resources:* knowledge management has become a key element in organizational learning, in order to ensure that the data and information is stored and easily extracted when people need it. Thus, databases play an important role to maintain information is available across the organization. Additionally, academic resources for large organizations that have the budget or external databases can help organizations to extract new information and learn from external resources that handle similar processes. The main objective of those external resources is that organizations learn and improve as a whole, as an industry, instead of getting partial learning in few organizations. In this sense, the industry fails in two different ways: First, the industry faces a competing and politicized environment [56], in which organizations are not willing to share their

lessons learned and best practices. Therefore, there is a lack of external information from which others organizations could learn. Secondly, even in the cases where the information is out there, organizations fail to understand the importance of those external tools and therefore people are either not aware of there existence or are not interested in using them. Finally, Organizations usually communicated external lessons learned from big incidents, but people see that type of incidents as events that could not happen in their own processes and therefore little attention is put into analyzing how those lessons learned are applicable to their processes and how that information could make their facility safer.

- *Validation of leading indicators:* process safety indicators provide evidence about the actual state of a particular process or activity. It helps organizations to get the right signals before an incident materializes and therefore, take appropriate actions to get the process back to normal. When an incident occurs, people involved in the process spend little or no time analyzing why they failed to get the right signals. Was the process giving the right signals? Were the indicators well defined? Why did operators fail to understand those indicators? These types of questions have to be answered after each incident investigation, in order to reevaluate the process, where the incident occurred and make sure operators can get all the required information and understand the process's behavior.

This research has focused in the analysis of four of the limitations mentioned above: ensure implementation of lessons learned, use and understanding of databases and academic resources, ensure sharing knowledge within the organization, and identification of root causes. The first three limitations have been addressed in this section. The last limitation: identification of root causes is covered in section 5.

4.2. DIKM model

In order to improve learning from incidents, it is required to ensure a corporate memory system within the organization, in which an organizational memory is present and knowledge is effectively transferred and maintained through generations. The Data-Information-Knowledge-Wisdom model (DIKM) fits the needs mentioned above and it has been widely used for many organizations to manage knowledge. The model describes the relationship among data, information, knowledge, and wisdom, and the transformation of each element to a higher level [102, 103]. Thus, the model represents how organizations can increase meaning and value as they go higher in the pyramid, as shown in Figure 12. An extensive literature about this model and knowledge management is available elsewhere [43, 104-106]. A summarized definition of each element is provided to understand the structure of the model and its link with the learning process.

- Data can be defined as values without context or interpretation. They can be symbols, signals or numbers with no structure [102, 103].
- Information can be defined as data that has been processed for a purpose. It is data that have been organized so it can have meaning for the user [102].
- Knowledge can be defined as the transformation of information, in which expert opinion, skills, and experience has been added. Knowledge is the synthesis of

multiple resources of information over time, in order to understand patterns and support decision-making [102].

- Wisdom can be defined as accumulated knowledge. It requires an understanding of principles, so it can be seen as an expert knowledge and judgment associated with the meaning of life [102, 103].

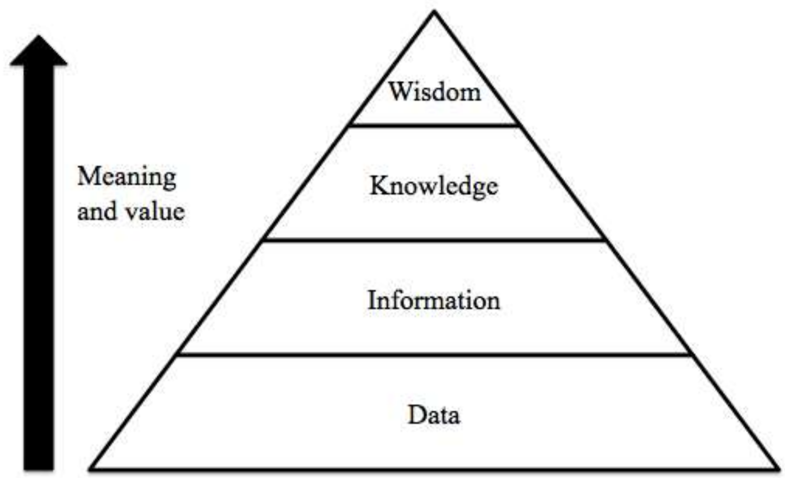

Figure 12 DIKW Model, adapted from [102]

This research has been focused only in one type of knowledge: safety knowledge. It converges technical, human and organizational aspects, that lead to influence people behavior and values. Thus, the learning process goal is to enhance, capture, refine, and implement safety knowledge so it can become part of the daily activities and culture of the organization. The DIKW theory has been used as basis to construct a framework to improve the learning process within an organization.

4.3. Learning process

Based on an extensive review of the available literature and benchmarking within oil and gas organizations, consulting companies and subject matter experts, a framework for the learning process inside an organization has been developed. The framework suggests a standardized approach to leverage the safety knowledge within an organization. It includes seven steps that should be followed in sequence in order to improve learning from experience. The steps included in the framework are intended to serve as a guideline for organizations that want to get a better understanding on how to obtain information and make it valuable. That is, transforming information into knowledge, by making it part of the organization and ensuring a corporate memory system inside of it.

In order to leverage the safety knowledge inside the organization, it is required to establish a corporate learning system, which should be owned by all employees in the organization. The system should be easily understood and accessed when required. The corporate learning system has two main objectives. First, make new information and lessons learned part of the organization. This means, to make those lessons learned part of the existing resources in the organization such as procedures and guidelines. In this context, people can have access to lessons learned related with the information that they are looking for and at the time they want it. This would help as a reminder about what can go wrong with the specific activity they are intended to perform. Second, the corporate learning system needs to support implementation and decision-making of new alternatives with the objective of making their facilities safer. To ensure that the information and knowledge that is being added will remain in the organization, it is important to document the whole process, make sure a proper management of change process is performed prior to any change, and link the reasons that support the alternatives. The last point is intended to ensure that people will understand the reasons of why the alternative was implemented at that time and the analysis behind it.

Most of the people involved in the organization are not even aware of where to find information and the potential benefits they can get from it. On the contrary, some people are aware about the available sources of information, but they do not know how to take advantage of this information. People inside the organization have access to a high volume of information but in many cases they do not have the time to identify which information is important, which information is valuable and should to be transformed into knowledge, and which information is not that relevant for them. As a consequence, people lose relevant information that can be applied to their facilities. People act based on what it is important for them and what they consider relevant for their work and would have a potential benefit for them. Therefore, transferring knowledge is a complex task, in which identifying the target and having a clear understanding of why it is important to them, becomes a crucial step to achieve learning. In this context, a lesson learned from an incident could be explained with technical detail to a supervisor, whom has the engineering background to understand the concepts involved on it. However, the same lesson learned has to be delivered in a different way to an operator, so he can understand and process the same information as the supervisor, without loosing the knowledge that is intended to be transfer.

Some organizations have spent a lot of effort developing sophisticated systems to store lessons learned and relevant information. Nevertheless, they fail to achieve the complete cycle, in which people within the organization own the system and understand it. The corporate learning system should be incorporated as part of the safety management system of the organization, the top management should support it, and all levels in the organization should be trained on it. The training would explain the benefits of it, the role of the corporate learning team and the people involved on it. Moreover, the training would give guidelines on how to use the Document Management System (DMS), when to use it and the type of information that can be extracted from it.

4.3.1. Corporate learning team

A corporate safety team should be in charge of managing the corporate learning system. The team has to be a group of subject matter experts with relevant knowledge in the processes, products and types of facilities inside the organization. The people in charge of the corporate learning system serves as a source of knowledge for the different facilities and people in the organization. In this context, they would be the bridge between the information and knowledge that need to be digested and implemented. Moreover, the team has the responsibility of filtering the information in order to ensure that the information that is being added is valid and reliable. It should be noted that the team is not intended to impose or enforce the implementation of lessons learned in the facilities, rather, the team is intended to guide facilities to get the right information and direct them in the right direction. The objective of the team is to support decision-making and provide the necessary resources to implement new alternatives. In this sense, the corporate learning team would be responsible to acquire new information, validate and analyze the applicability, disseminate the information to the intended targets, ensure the availability of the information, and support implementation as required.

It is important to notice that a single team of experts it is not enough to determine what information is relevant for the organization. In addition, it is not possible to have the level of expertise in all areas of process safety. Thus, a pool of experts in different areas within the organization should be linked with the corporate learning team, in order to provide support in the analysis and selection of potential knowledge that should be acquired by the organization. In this sense, the pool of experts would serve as a guideline or consulting assistance for the corporate learning system.

4.3.2. Flow of information

Information and knowledge are important components in the management of any safety system. The system has to ensure the availability, accuracy and updated knowledge, in order to support the learning process and decision-making. Inside the system two different types of information can be identified: internal and external information. Internal information refers to the information that is created inside the organization, such as incident investigation reports, best practices and performance indicators reports. Conversely, external information refers to the information that is obtained from agencies, databases, academic resources and other organizations. This information can be lessons learned, new standards, best practices, recommended practices, *etc*.

The corporate learning system has the challenge to effectively manage all channels and types of information at the right time and to the right target. Therefore, the system should be supported by a Document Management System (DMS), in which all the information would be uploaded easily and extracted as needed. In addition, the DMS needs to keep the information up to date and link the new information with the existing documents of the organization.

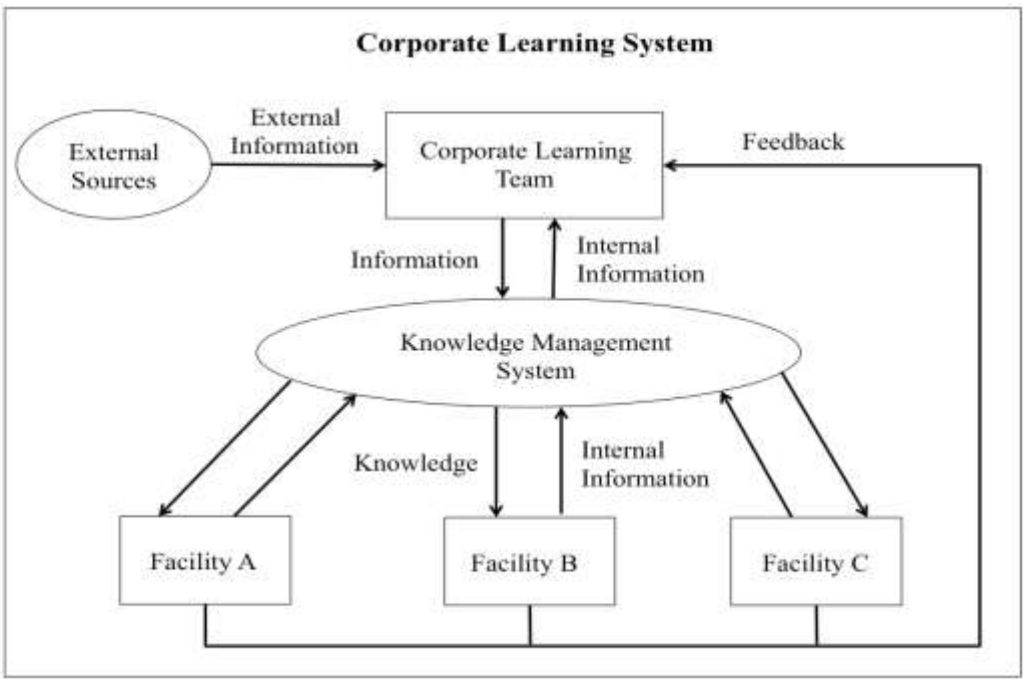

Figure 13 Flows of information in the corporate learning system

In this context, the corporate learning system would acquire internal and external information, which is going to be analyzed and validated by the corporate learning team. The relevant information would then be incorporated into the DMS and linked to the existing documentations as required. Then, the team together with representatives of each facility, in which the knowledge is intend to be transferred, would work together to determine the best approach to implement that knowledge into the facility. After implementation, the facility would provide some feedback to the corporate learning team to ensure continuous improvement and verified the effectiveness of the process. At the same time, each facility is responsible for providing internal information to the system to assure that the information is analyzed for different facilities across the organization and it is not just communicated. This flow of information is shown in Figure 13.

4.3.3. Learning process description

The learning process consists of seven steps: enhance internal information, acquire information, assess alternatives, define metrics, refine alternative, implement alternative, and monitor performance. The process describes how the corporate learning system would work and the key elements that need to be considered in each step. The first two steps refer to the acquisition of relevant data and information into the system and the last five steps refer to the transformation of that information into knowledge. A diagram of the process is shown in Figure 14.

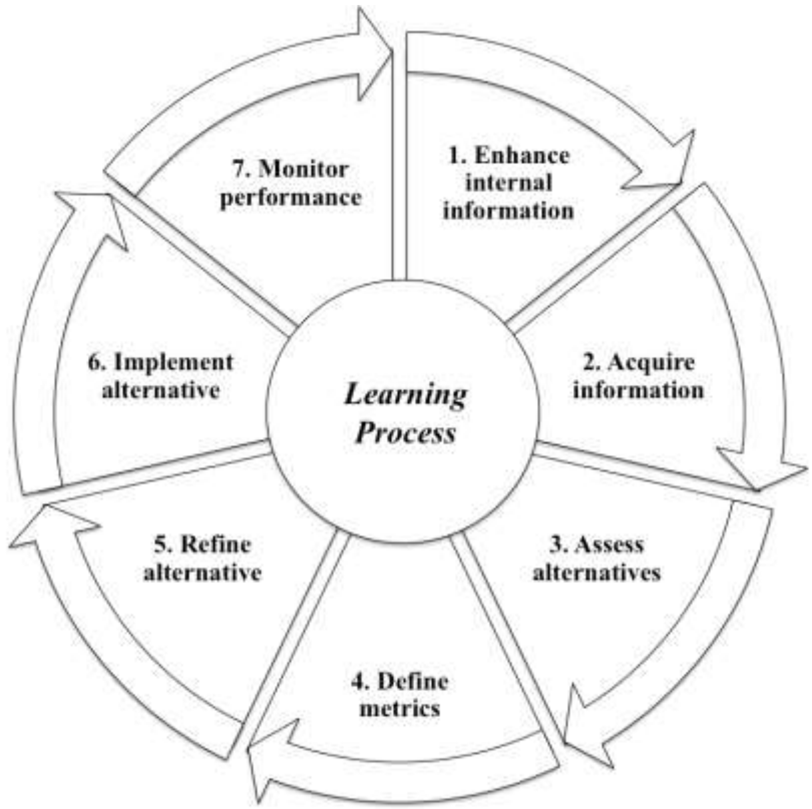

Figure 14 Learning process

4.3.3.1. Enhance internal information

Enhance internal information refers to the process in which the incident investigation process and final product of is improved by the incorporation of additional steps in the process. Its goal is to provide a more detailed analysis of the incident and the safety management system of the area where the incident occurred. The process is enhanced through the investigation of all incidents with significance, the review of previous internal incidents and similar external incidents, the revalidation of performance indicators of the process, and the identification of failures in the management system. Additionally, this step support organizations to effectively identify organizational, design and cultural failures instead of human errors as root cause of incidents. This step is explained in detail in section 5.

4.3.3.2. Acquire information

Once the organization can rely on the internal information that is created inside of it, the next step is to acquire additional information from different sources. In this sense, it is important to identify the potential sources from which relevant information can be extracted. As explained previously, there are two types of sources: internal and external. Internal information would be acquired from the different facilities within the organization. Likewise, internal information would be gained from all branch offices around the world that are part of the same organization. This information would be primarily lessons learned from incident investigations. However, information such as best practices and trend analysis reports can be considered as well. External information opens a wide window of opportunities from where new information can be acquired. The primary source of information would be available databases. Nowadays, there is still no single database available, which can provide full access to a large number of incidents in the chemical and oil and gas industry and, at the same time, have all the desirable features such as easily searchable, public, with multiple filters options, and with detailed analysis reports. Therefore, it is necessary to use a combination of multiple databases. Regulatory agencies such as the Environmental Protection Agency (EPA) have their own database, from which information regarding toxic releases can be found. The Chemical Safety Board [6] provides detailed analyses of process safety incidents. However, the amount of incidents investigated is limited. Some public databases such as eMARS developed by the Major Accident Hazards Bureau (MAHB) provides incidents reports involving highly hazardous substances. Likewise, private databases such as Process Safety Incident Database (PSID) created by CCPS, provides incidents reports for organizations participating on it. Additional information can be acquired from external associations like the American Petroleum Institute (API) and the National Fire Protection Association (NFPA), which provides guidelines for standards and best practices. Finally, large organizations that have the budget also have the opportunity to established partnership with academic entities in order to be involved and have access to trending investigations from first hand. This type of partnership can be established with universities like Texas A&M, which houses Mary Kay O'Connor Process Safety Center. It is evident the wide area from which safety information can be extracted. Thus, it is important that the corporate learning team set the basis and defines the scope and objectives of it. Moreover, those objectives have to be aligned with the organization's goals and business priorities.

4.3.3.3. Assess alternatives

Once the team has prioritized the alternatives that could be valuable for the organization and fit the needs of it, they have to identify the potential processes, facilities or business areas, where the alternative could be applied and would gain benefits from it. Those relevant installations are the potential target, where the information could be translated into knowledge and consequently be implemented into their processes. During this process the corporate learning team has the responsibility of determining and classifying the potential targets and the channels of communication that are going to be used during the process. The information can be communicated into two different approaches: sharing the information or transferring the information. Sharing the information refers to the communication to an arbitrary receiver. In this case, it would be facilities that might be interested in the information but no action is required from them. Conversely, transferring the information refers to the communication to a specific receiver, who in this case would be facilities in which the new or alternative information could be implemented and the potential knowledge is intended to be transferred.

Transferring the information requires a high level of commitment from the different facilities that have been selected as potential targets. From this point, a member or members of the corporate learning team would meet with some representatives of the potential target and would work together in the analysis of the alternative. Through meetings the objective is to communicate the alternative and the assumptions that have been made in order to determine why it is applicable for them. Then, they would evaluate together the applicability of this alternative to their process, by analyzing the potential benefits, costs and risk associated with the implementation or not of the alternative. This process has to be documented and the final decision has to be supported. It is important to mention, that the objective of those meetings is to take the time to really analyze the alternative, rather than enforce the implementation of it. At the end, the final decision would be made by each installation. Not all alternatives have to be implemented because in some cases the alternative would be not feasible to implement to that specific process or they are just handling the risk with different alternatives that are valid as well.

Some alternatives can be applied across the organization and do not require the identification of potential targets. Therefore, for those alternatives the corporate learning team should develop an action plan and execute it as part of their job. One example for this type of alternatives can be a modification to a procedure that is applicable to all facilities. In this context, the team together with a subject matter expert would be responsible for making the required changes, documenting the changes, incorporating them into the DMS, communicating it and ensuring training as needed.

4.3.3.4. Define metrics

This step requires asking the questions of how they can validate what they want to achieve? How they can know the alternative is operating as expected? Defining performance indicators allow people to verify the system behavior and measure how much it has been changed with respect to the initial set point. Indicators should be determined prior to implementation in order to have a clear picture of what they want to achieve with it. Likewise, it would help to verify the results since initial phases. Indicators would change depending of the actual phase of the alternative and would give real data to determine if the alternative is giving the expected results.

Conversely, indicators for the corporate learning system should be determined as well, to evaluate the performance of the system and identify improving opportunities for it. In this sense, indicators to analyze how the system operates, personnel performance, feedback and results of the system should be defined and evaluate periodically.

Indicators such as the number of identified alternatives vs. the number of alternatives implemented, percentage of people trained on how to corporate learning system works and how to take advantage of it, percentage of alternatives that are rejected by the facilities, the number of deficiencies identified in the system, or number of management review of the system can be used as metrics for the system.

4.3.3.5. Refine alternative

Defining metrics and refining the alternative should be performed at the same time, because once the facility is fitting the alternative to their own processes, some modifications or alterations to the initial idea might be necessary. However, initial metrics have to be determined to set the general goal of the alternative. Refining the alternative refers to the process in which the facility has to define the limitations, assumptions, boundaries and required resources based on their own needs and capacity. Similarly, refining the alternative requires to perform a management of change process in order to determine the potential impact to the process and people and the additional considerations that need to be made prior implementation. Finally, an action plan has to be developed, in which a detailed list of tasks, timeline and resources should be evidenced.

4.3.3.6. Implement alternative

Implement the alternative refers to the actual execution of the action plan that has been proposed by the facility. Each facility would be responsible for the execution and verification of it. However, the corporate learning team should verify periodically its current status. Likewise, the corporate learning team would support the whole process based on what has been agreed during the evaluation phase of the alternative.

4.3.3.7. Monitor performance

Monitor performance refers to continuous improvement to validate and refine the implemented alternatives and corporate learning system. At this point, a detailed review should be performed to verify if the knowledge was successfully transferred, if the knowledge was appropriate, was analyzed in detail, accurate criteria was used, and the expected benefits were achieved. Moreover, the team has to analyze if the implementation was performed as expected and what can be improved from it. Based on the improvement opportunities that have been found during this analysis, the alternative can be improved and refined as needed or can be modified if the expected results were not successfully achieved. Additionally, the corporate learning system should be validated in order to determine if the process has been successfully implemented across the organization. In this analysis the corporate learning team should evaluate if the objectives have been achieved, if people are fully committed with the system and feel part of it, if the organization is getting the right knowledge, if the level of competence in the team is adequate, and how the cycle and each phase of it can be improved.

4.4. Additional elements to achieve organizational learning

In the learning system presented in the first section of this section, three types of learning were identified: individual, organizational and industrial learning. Learning is achieved through the small entity to a bigger one. In this case, industry learning only can be achieved once and organizational learning has been achieved. Similarly, organizational learning is achieved once individual learning has been achieved for people involved in the organization. Even though this research has been focused on the understanding and improvement of organizational learning, it is important to mention that achieving individual learning becomes an essential part of achieving organizational learning. Therefore, organizations need to provide the necessary tools and resources in order to support and enhance individual learning for all employees. As a result, individual learning collectively is transformed into an organizational learning and at the same time, an effective organizational learning is able to support each phase of employee's individual learning as presented in Figure 15.

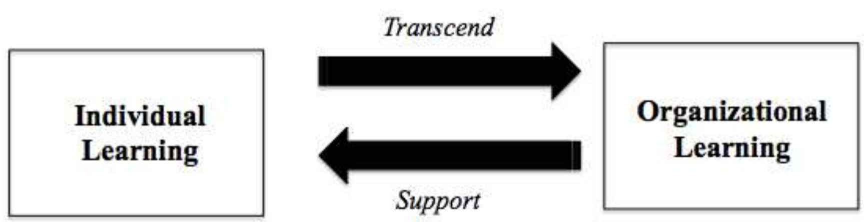

Figure 15 Improving organizational learning

Supporting the individual learning can be achieved through the development of corporate learning systems in which the knowledge is being managed within the organization and a learning environment is encouraged, as been discussed in the previous sections. Conversely, transcending the individual learning to an organizational one requires the implementation of adequate training programs and supporting techniques, which enables people to individually acquire new information, analyze it and apply it into their daily jobs. Some of these elements are briefly discussed below.

4.4.1. Effective training programs

Developing and delivering effective training programs ensure the basis for a successfully corporate learning system, which enables employees to gain an understanding of the main goals, structure, and expectations of the organization. Thus, an effective training program should address the following elements:

- Detailed training needs matrix for all employees' position in the organization.
- Specific qualification criteria for trainer's selection. These criteria should include the necessary technical knowledge that is intent to be transferred as well as the necessary soft skills such as good communicator, presentation skills, able to open healthily discussions, *etc*.
- Expectations, goals and final product of each training course.
- Up to date training material, which covers all relevant technical knowledge and can be easily understood for the trainees.
- Required tools, resources and infrastructure to perform the predefined training courses.

4.4.2. Effective training courses

As discussed in section two, organizations should apply different training techniques in their training programs based on the predefined expectations of the course and the current needs of the organization. Although lectures methods are the most common applied technique in most organizations, this method is not able to support skills and attitudes development. Thus, it is important to recognize the use of multiple training techniques in order to be able to provide a successful training program, which enables employees to acquire and develop knowledge, skills, and attitudes. Similarly, higher levels of retention' techniques such as group discussions and practices cannot be fully achieved without the understanding and analysis of the theory behind it. For instance, organizations can implement the use of simulators to teach operators how to perform a specific task and achieved the necessary skills to perform it. However, if the use of simulators is not supplemented with additional training techniques such as lectures, readings, and discussions, it is likely that the operator is not going to be able to make decisions on his own once he experiences an abnormal situation during his real job. The operator would not have the required technical knowledge and analysis to understand the process behavior and potential outcomes of it.

Once the training techniques have been defined, it is also important to structure the development of the course and the elements that trainers must take into consideration during the preparation, execution, and evaluation of the course. First, trainers have to determine the objectives of the course; this requires the understanding of the target and their motivation. In this sense, the challenge is to identify why is this new knowledge relevant to them, instead of thinking why it is important for the trainer or the organization. This with the objective of answering the questions: do they want to know that? Or do they need to know that? And based on it, trainers can take the best approach for creating ownership about the knowledge that is being taught. Secondly, the development of the course should be problem-solving oriented in which they are able to analyze situations and make decisions about it. In addition, it should encourage trainees to seek for more information and create spaces where they have to explain to others what they are learning. This would allow trainees to digest the information and take the time to consolidate this knowledge and fitting it into their existing knowledge. Thirdly, each lesson has to clearly identify the benefits trainees can get for it in order to maintain their motivation. Likewise, it is always a good approach teaching with examples because this enables them to be familiar with the situation and recreate this new knowledge into their own situations, and at the same time, it increases trainer's credibility. Finally, trainees should receive constant feedback during the development of the course and an assessment should be incorporated as part of the process to help trainees refresh concepts and identifying the key elements of the course. This assessment should be problem-solving oriented [107-109].

4.4.3. Supporting unlearning processes

As Pighin and Marzona stated, "unlearning is defined as throwing away concepts learnt in the past to give space for possible new learning" [110]. In this sense, organizations should support employees in the transition from the old knowledge to the new one and provide the required tools and resources to make the transition easier at both individual and organizational level. In the process safety field more attention have been given to the development of management of change programs in order to ensure that risks are controlled once the organization makes changes in their facilities, operations or personnel. However, less attention has been given to the cultural and organizational factors, as well as the individual impact that may be influenced by those changes. Therefore, management of change programs should incorporated individual, organizational and cultural aspects that may be also influenced by the changes that are made in the organization. The unlearning process can help organizations to identify the potential impact of those changes and provide the corresponding plan to overcome the resistant to changes attitudes that may arise from learning processes.

Some of the elements that people who are intended to transmit the new knowledge should take into account are briefly discussed below. First, the acquisition of new knowledge is not always an easy process for some employees, and it is even harder when they have been doing their job in a particular way for many years. Therefore, it is important to identify the potential impact of this change (new knowledge) and develop mitigation actions to overcome these factors. Secondly, it is essential to understand that there is going to be resistant of change because it is part of human behavior and it cannot be prevented. But at the same time, it is important to note that the resistant of change can be temporary if proper actions are taken to manage it. Thus, instead of having a negative attitude of what employees are going to say or how they are going to complain about it, organizations should be focusing on predicting those behaviors and developing corrective actions for those attitudes. Thirdly, once the person in charge of transmitting the new knowledge is in contact with the target, he has to explain to them the requirements of the process. This means, to explain why this change is necessary for the organization and why this new knowledge is important for them, instead of start explaining how to perform the new task or going in detail to the technical part. This step gives them the opportunity to analyze how these new requirements fit into their existing knowledge and potentially identify some gaps during this process. Finally, the new knowledge can be transmitted, follow by the identification of resistant to change attitudes and the implementation of corrective actions. This process should be performed over and over again until the new knowledge has been consolidated in all employees involved in the process [110].

5. ENHANCE INTERNAL INFORMATION

In this section, the first step of the learning process *enhance internal information* is introduced in detail. This section presents the incident investigation process throughout the development of a task analysis in order to analyze the relationship among the people, the task, and the environment for a specific task. The corresponding results were then used to enhance the existing incident investigation process by the incorporation of additional steps into the process. Finally, a description of each of the incorporated steps is provided.

5.1. Task analysis

A task analysis is performed with the objective of enhancing the understanding of how the people, environment, and task work together and how the system is supporting this process [111-113]. A hierarchical task analysis has been developed for the incident investigation process to analyze the task's objectives in this process, the people involved in it, the complexity of the task and the expected goals for each stage in the process. The general structure of an incident investigation process involves the following steps: reporting, collecting evidence, analyzing evidence, identifying the causes of the incident, developing recommendations, and sharing lessons learned. A more comprehensive description of the incident investigation process has been presented in section 3. The incident investigation process has been divided into subtasks and the most challenging tasks have been selected for further analysis. Each category has been broken down into more detail tasks to understand specific goals of each step of the process. Nine subtasks have been selected for detailed analysis in which the common errors were determined. Finally, the general characteristics of the people and environment for the selected subtask were discussed.

5.1.1. Hierarchical task analysis decomposition

Figures 16-18 present the hierarchical task decomposition for the incident investigation process. The steps highlighted in gray represent the subtasks that have been considered the most complex and challenging in the process. Thus, a further analysis has been performed in the next section. The following subtask were selected:

- Report incident
- Select investigation team
- Visit scene:
  - Interview witnesses
  - Gather preliminary evidence
- Analyze evidence
- Apply incident investigation methodology
  - Identify root causes and contributing factors
- Develop recommendations
- Define responsible and resources
- Monitor status of recommendations

5.1.2. Hierarchical task analysis results

Tables 1-7 present the results obtained from the hierarchical task analysis.

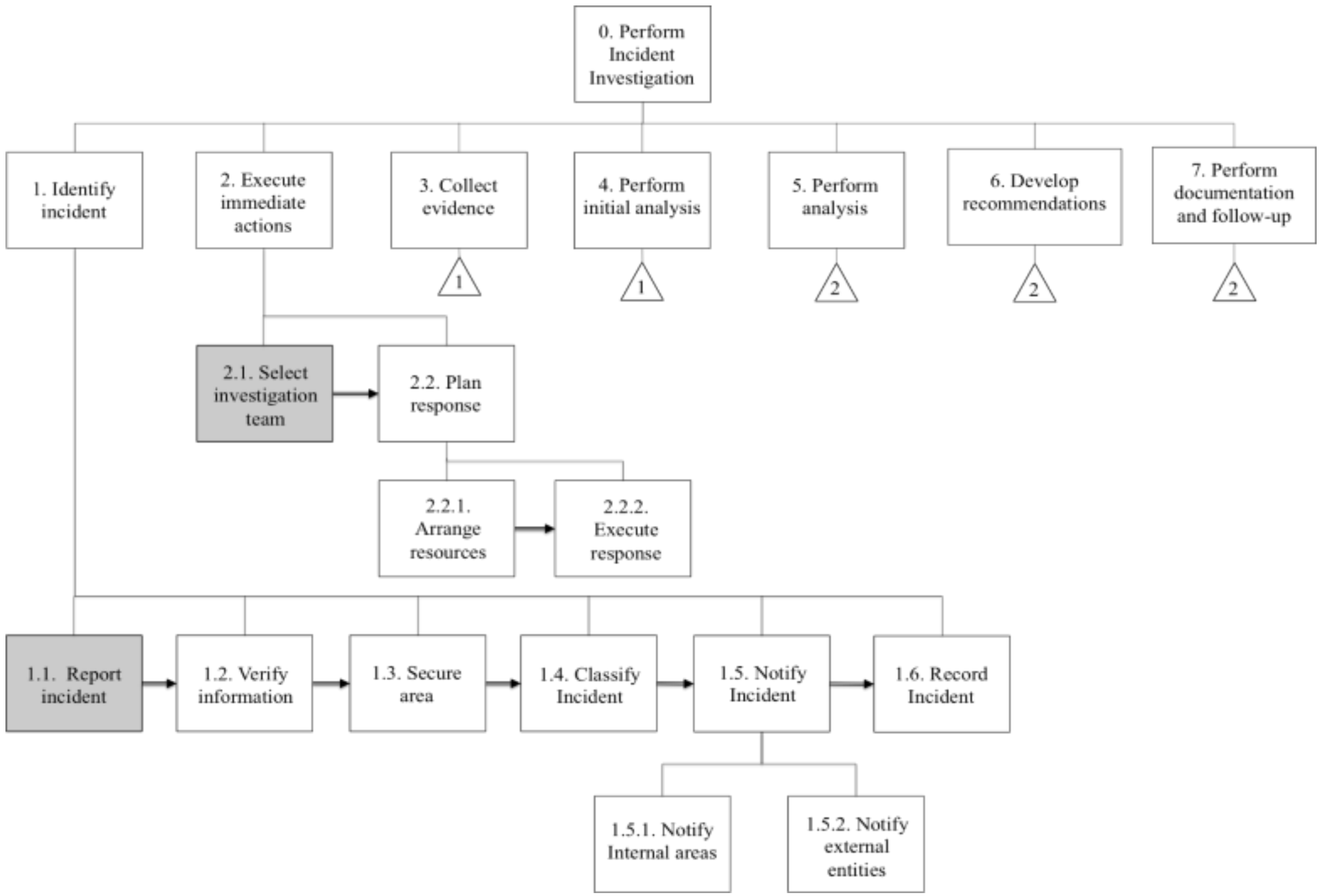

Figure 16 Task analysis decomposition part 1

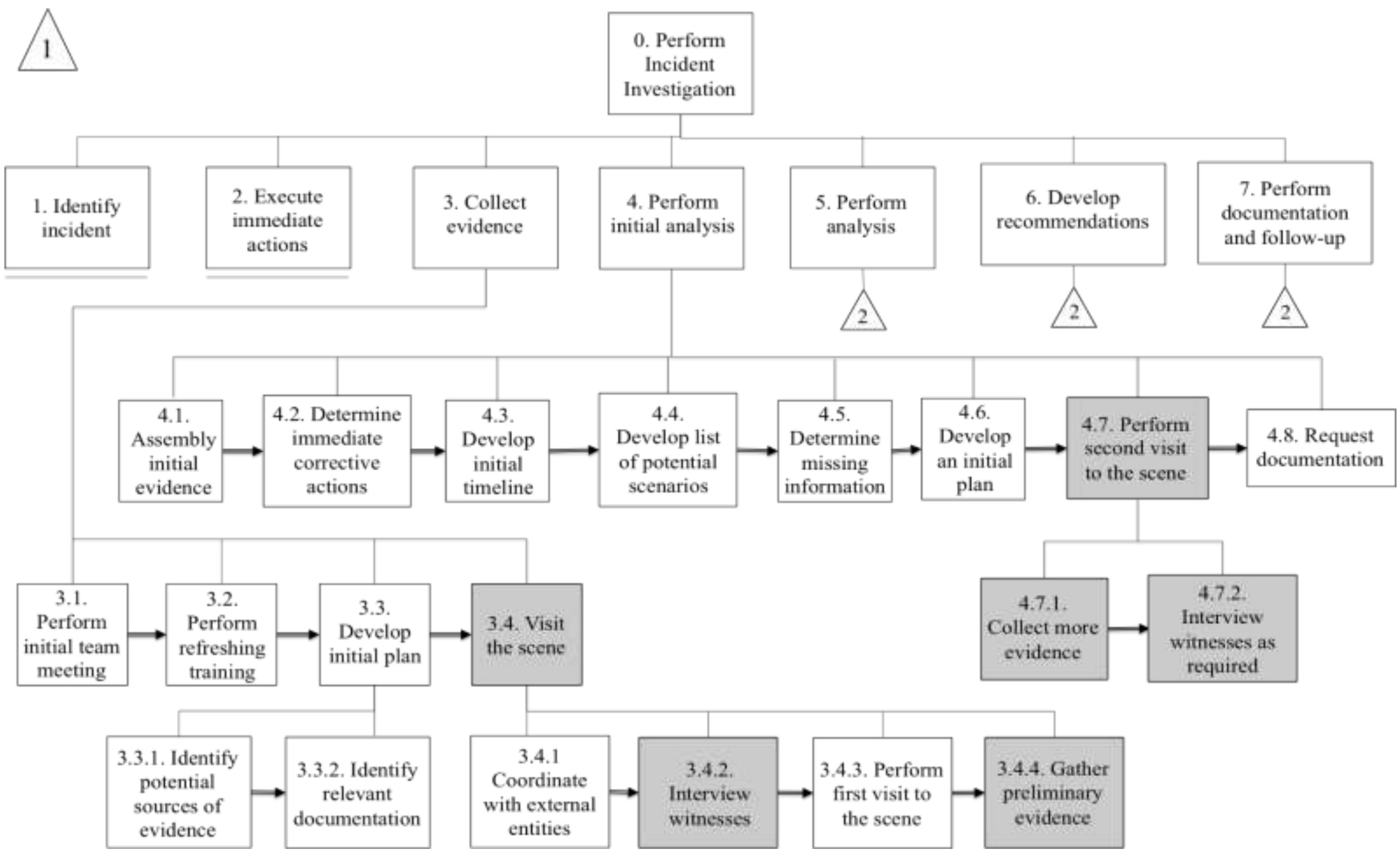

Figure 17 Task analysis decomposition part 2

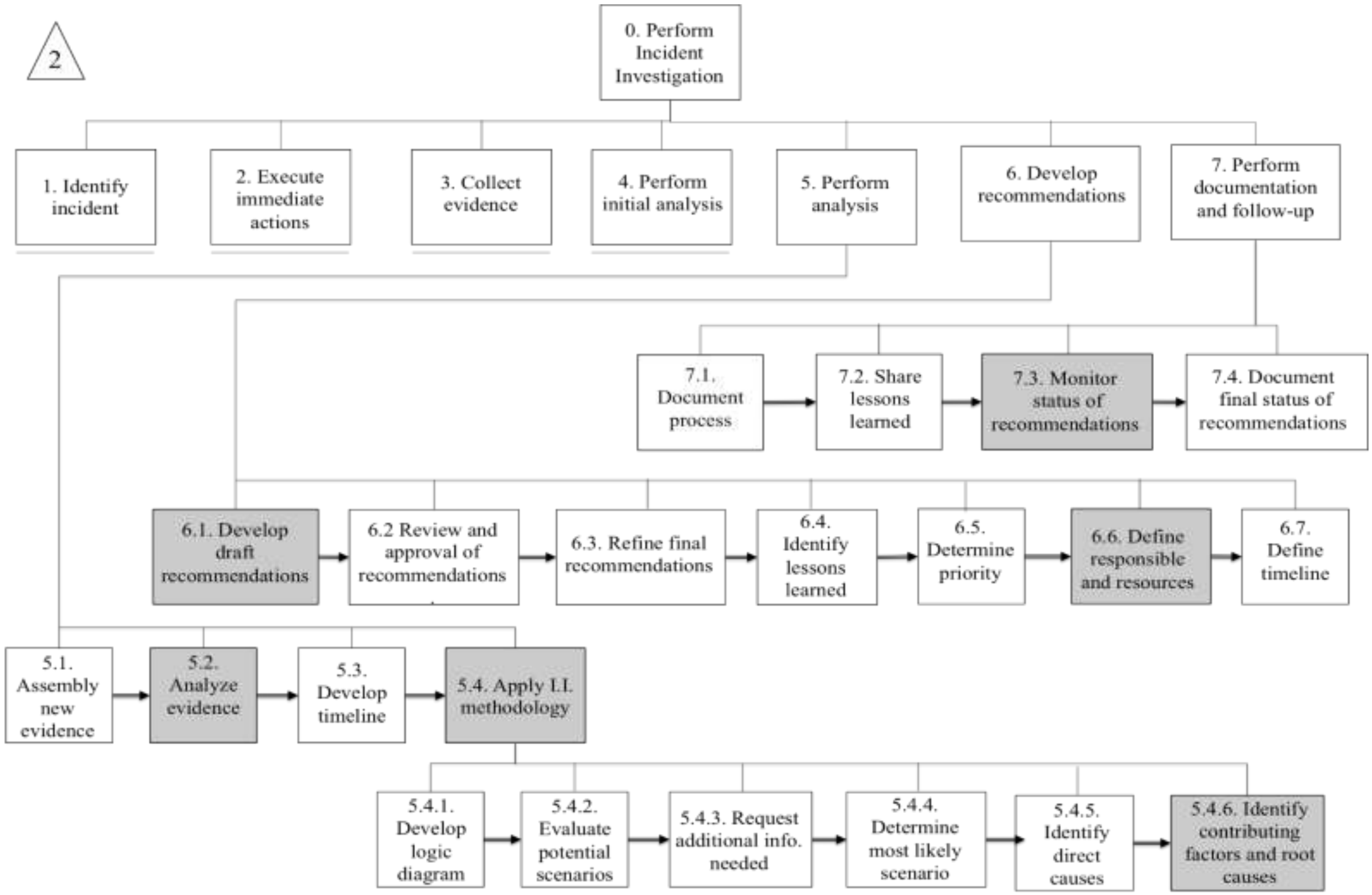

Figure 18 Task analysis decomposition part 3

Table 1 Hierarchical task analysis part 1

Task	People	Environment	Why is Challenging?	Common Errors
Report incident	Employees	Varies depending of the safety culture Mechanism for reporting Level of engagement of the top management	Requires a strong safety culture within the organization Employees have to be engaged with their work The organization has to ensure an open and healthy reporting environment in which individual blame is avoided Employees feel that they are going to lose their jobs	Tendency to cover up mistakes Employees fail to understand the benefits they can get from the investigation of incidents Top management tends to blame employees
Select investigation team	Safety Department Management	Pressure against time Level of engagement of the top management Working with others to make decisions	Requires a pool of trained people in incident investigation Availability of personnel (100% of their time for a short period of time) Based on the complexity of the system where the incident occurred, specific expertise is required	Select investigation team based on availability of personnel Selected people have little or no training in incident investigation process Required expertise in the team is ignored

Table 2 Hierarchical task analysis part 2

Task	People	Environment	Why is Challenging?	Common Errors
Interview witnesses	Incident investigation team	Pressure against time External entities involved in the process Working with new people to make decisions High volume of pressure, emotions, and uncertainty The incident investigation team set aside their routine work The investigation is a temporary job Different types of witnesses: Employees, usually operators that are part of the process	Witnesses' availability Memory recalls change over time Witnesses may be affected by a combination of emotions The information may not be accurate and witnesses may have different versions of the same incident Witnesses can make wrong assumptions	Inexperienced people performed interviews Tendency to blame employees The interviewer attempts to get what he thinks happened instead of listening what the witness have to say Witnesses bias: they say what they think happened or hide facts they do not want to tell

Table 3 Hierarchical task analysis part 3

Task	People	Environment	Why is Challenging?	Common Errors
Gather preliminary evidence	Incident investigation team	Pressure against time External entities involved in the process Working with new people to make decisions High volume of pressure, emotions, and uncertainty The incident investigation team set aside their routine work The investigation is a temporary job Complexity of the system where the incident occurred	The site may be severely damaged External regulatory agencies may have control of the site making access difficult Some physical evidence degrades with time Degree of difficulty of understanding of the incident during the analysis phase	Loss of relevant evidence

Table 4 Hierarchical task analysis part 4

Task	People	Environment	Why is Challenging?	Common Errors
Analyze evidence	Incident investigation team	Pressure against time External entities involved in the process Working with new people to make decisions High volume of pressure, emotions, and uncertainty The incident investigation team set aside their routine work The investigation is a temporary job Complexity of the system where the incident occurred	Requires expertise in incident investigation methodologies Requires expertise in the process where the incident occurred, the chemical involved, and the organization It is hard to make assumptions about what happened Some evidence may be missing. Pressure from different departments Degree of difficulty of understanding of the incident during the analysis phase	Incorrect assumptions Insufficient evidence to select the most likely scenario Inadequate incident investigation methodologies and procedures Insufficient analysis and time spent on it

Table 5 Hierarchical task analysis part 5

Task	People	Environment	Why is Challenging?	Common Errors
Identify contributing factors and root causes	Incident investigation team	Pressure against time External entities involved in the process Working with new people to make decisions High volume of pressure, emotions, and uncertainty The incident investigation team set aside their routine work The investigation is a temporary job Complexity of the system where the incident occurred	Requires expertise in incident investigation methodologies and analysis Requires expertise in the process where the incident occurred, the chemical involved and the organization Pressure from different departments Degree of difficulty of understanding of the incident during the analysis phase	Identification of intermediary causes as root causes of the incident Improper analysis of results

Table 6 Hierarchical task analysis part 6

Task	People	Environment	Why is Challenging?	Common Errors
Develop recommendations	Incident investigation team Management	Pressure against time External entities involved in the process Working with new people to make decisions High volume of pressure, emotions, and uncertainty The incident investigation team set aside their routine work The investigation is a temporary job	Reach an agreement with all the different groups of interest Recommendations have to respond to each identified cause in an effective manner Investigators can write ambiguous or unclear recommendations	Superficial recommendations Unrelated recommendations with the identified causes of the incident Ambiguous or unclear recommendations

Table 7 Hierarchical task analysis part 7

Task	People	Environment	Why is Challenging?	Common Errors
Define responsible and resources	Safety Department Management	Pressure against time and resources Level of engagement of the top management Working with others to make decisions	Employees' availability Budget is limited There is no time for extra work Top management has to be engaged. Requires a strong safety culture within the organization	Inadequate risk-ranked of recommendations Inadequate top management engagement Inadequate distribution of resources
Monitor status of recommendations	Safety Department Management	Pressure against time and resources Level of engagement of the top management Working with others to make decisions	Recommendations' status is easily forgotten Top management and employees have to be engaged Requires a strong safety culture within the organization	Recommendations are forgot and therefore are never implemented Recommendation' status is only responsibility of the safety department

5.1.3. Subtasks analysis

Since each incident investigation is a new process, the people involved and the environment is always changing depending on the severity of the incident and the unit where the incident occurred. In addition, the number of people in charge of the investigation, their backgrounds and previous experience regarding incident investigations would vary as well. Furthermore, the frequency of this task cannot be determined, since it would depend on the number of reported incidents and the type of incident. In the incident investigation process three groups of people were identified: employees who perform the task of reporting incidents, safety department and management, and the incident investigation team. Each of this group of people executes different stages during the incident investigation process and has different attributes. Therefore, they need to be considered separated.

5.1.3.1. People: employees

- Task: report incident
  - People that work within the organization and perform a specific task on it. Employees have different levels of education and backgrounds. However, employees are expected to have the same training regarding policies, values and goals of the organization. Additionally, employees are expected to have some preliminary training and/or awareness campaign regarding incident reporting.
  - Employees spend eight or more hours per day in their jobs. Reporting incidents is considered as an extra task besides their routine work.

- Employees need to be motivated and understand the benefits of it in order to report an incident.
- Employees need to have general knowledge regarding safety and how to report an incident to perform the task.
- No skills are required to perform this task.

5.1.3.2. People: safety department, management

- Tasks: Select investigation team, define responsible and resources, monitor status of recommendations
  - The tasks mentioned above are specific tasks that are performed in conjunction with two different groups of people: the safety department and the top management. The combination of both gives the necessary background in process safety and management to support decision-making. Thus, the safety department is in charge of providing expertise in the selection of personnel and determining the required resources to perform the investigation. Conversely, the top management is in charge of providing the required resources and ensuring personnel availability.
  - Their role is primarily decision-making to ensure that the investigation is executed with the right people, resources and time.
  - The safety department should have expertise in process safety and incident investigation in order to determine the severity of the incident and resources needed.
  - The top management should have knowledge in business and safety priorities, as well as the available budget in the organization to support decision-making.

- Both groups of people should have strong communication and leadership skills to coordinate different groups of people and make decisions within a short period of time.

5.1.3.3 People: incident investigation team

- Tasks: Interview witnesses, gather preliminary evidence, analyze evidence, identify contributing factors and root causes, develop recommendations
  - The people that are part of the incident investigation team are usually employees who have to suspend their routine job and perform the investigation as a temporary job. Thus, people have to perform the task within a short period of time and under a lot of pressure.
  - The team is composed of different background and experience, which enables the understanding of the incident by the combination of expertise. Depending on the nature of the incident the incident investigation team would vary and different types of background would be involved, such as engineers, safety specialist, maintenance operators, contractors, lawyers, *etc*. Therefore, the people involved usually have never worked together before.
  - Each member of the team needs to be trained in incident investigation and if possible, having previous experience in incident investigations.
  - People within the team should have communication and leadership skills in order to collect evidence, interview people and support the analysis process.
  - The team has to have a strong technical knowledge about the process where the incident occurred and the chemicals involved.

- At least one of the members of the team should have a strong background in incident investigation methodologies and root causes identification.

5.1.3.4. Environment

To perform this task successfully, it is required to have a strong safety culture within the organization in which employees and the top management are engaged with it and an open and healthy reporting environment is encouraged. Similarly, depending on the level of engagement of management and employees, the right amount of resources and time would be spent during this task.

The environment where the task is performed is the facility where the incident occurred. These are chemical and oil and gas facilities such as refineries, platforms, onshore facilities, *etc*. The investigation is executed at the same time that employees are performing their job or some of them may be recovering from the consequences of the incident. Furthermore, the unit where the incident occurred may be destroyed or heavily damaged by the incident, making it difficult to have access to the information.

Reporting the incident is executed depending on the available tools that the organization has for reporting incidents. This can be verbal reporting, written forms or electronic forms. Likewise, the investigation analysis is executed depending on the available tools and training within the organization. These tools refer to the incident investigation methodologies that the organization has established depending on the severity of the incident. Additional tools are the available procedures and guidelines for the protocol prior the investigation, the development of the investigation, and required post-activities.

5.1.4. Task analysis remarks

The task analysis developed for the incident investigation process gives more relevant insights of the process. First, the quality of the investigation is proportional to the level of training, previous experience performing the same task, and level of expertise of the incident investigation team. Thus, organizations should have a pool of experts in incident investigation methodologies as well as incident investigation processes. Likewise, it is important to gather the right level of technical knowledge based on the type of incident and its significance. Secondly, the safety culture of the organization plays a fundamental role in the success of investigations, because it determines the number of incidents that are going to be reported, the resources availability, time spent, and engagement of the top management, as well as employees who are in charge of the execution of recommendations. Similarly, the safety culture will determine if recommendations are implemented and the whole incident investigation process is completed. Third, communication, teamwork, and leadership skills are significant contributing factors in the process. These skills enable the team to organize relevant information, interview people, analyze the incident and work together in the development of recommendations. In addition, these skills enable the team to complete the investigation on time and with sufficient analysis. Finally, developing recommendations was identified as one critical task in the process because it converges all the effort and knowledge spent into the analysis. Moreover, recommendations are the final output of the investigation. Therefore, the quality of it is going to be measured based on the feasibility, clearness, and adequacy of the recommendations.

Additionally, the task decomposition and analysis of it identified some of the limitations of the process and improving opportunities on it. Since the environment and people involved in the investigation are always changing, the organization miss valuable information that can be used in future incident investigations. As a result, each investigation is a new process in which the learning curve has to start from zero each time. This gives the opportunity to enhance the process by the incorporation of knowledge from previous incidents and extracts this knowledge for the incident that is being analyzed. Similarly, the current incident investigation process does not support the identification of required changes in the management system, which enables organizations to identify cultural, management conditions, and system deficiencies that increase the risk in the organization. Furthermore, the training material is not updated in order to ensure a complete learning cycle of the incident. Moreover, the re-evaluation of leading indicators of the process is not considered in the incident investigation process.

5.2. Proposed incident investigation process

Enhance internal information refers to the process in which the incident investigation process is conducted and the final product of it have been analyzed and additional steps have been incorporated into the process. The objective is to provide a more detailed analysis of the incident and the safety management system, where the incident occurred. Since incident investigations are one of the most powerful practices to learn from experience, organizations need to focus their attention on improving their incident investigation management programs to provide high-quality recommendations and ensure that organizational and cultural failures are identified [77, 91]. Incident investigation process refers to the sequence of stages addressed after an incident happens. Starting from the report of the incident, followed by the collection of evidence, incident investigation analysis, development of recommendations, communication of lessons learned, and follow-up of recommendations [80, 81]. Regardless of the incident investigation method used, the main structure remains constant. Thus, organizations miss valuable information that should be analyzed during this process such as previous incidents, leading indicators of the process, how the identified gaps fit into the current training material, and how to incorporate this learning into the management systems of the organization. Figure 19 presents a modified incident investigation process, in which additional steps have been incorporated into the traditional process with the objective of providing additional sources of information into the investigation. The grey boxes in the figure represent the steps that have been included, while the white boxes refer to the original structure of the incident investigation processes.

After an incident occurs and is reported, the significance of the incident has to be determined. This refers to the categorization of the incident in which the potential impact of the incident is evaluated. Based on this result, the level of detail in the analysis and the complexity of it are determined. This means if simple methodologies and/or trend analysis are sufficient or a detailed analysis is required. Then, the collection of information and evidence has to be performed. This stage would determine the quality of the identified causes and recommendations [80]. Once the information has been collected, the incident investigation analysis is developed. In this stage incident investigation methodologies are implemented for the reconstruction of events, the identification of critical and causal events and the identification of root causes of the incident.

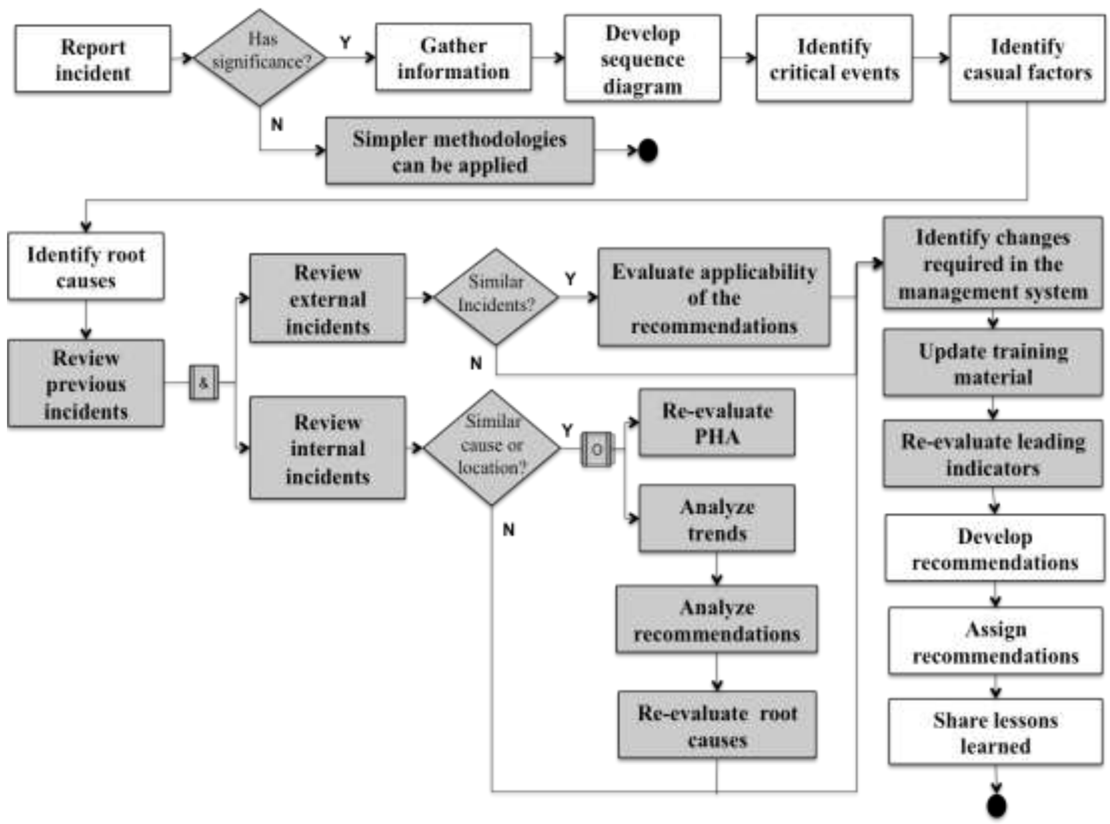

Figure 19 Proposed incident investigation process

The following steps suggest a detailed analysis of previous internal and external incidents from which valuable information can be extracted. The analysis of external incidents gives the opportunity to retrieve missing lessons learned that the organization failed to learn. Thus, the applicability of those lessons learned can be evaluated into the process. The objective of reviewing external incidents is not only to analyze the applicability of their recommendations to the incident that is being analyzed. It is also to analyze the current practices that others organizations are implementing, compare their own technology with respect to others organizations, and extend their existing knowledge regarding national and international standards and best practices that may be applicable to their facilities. Moreover, review of external incidents serves as support to explain the causes of the incident to the interested parties. This means helping build trust and credibility with regard to the results that the incident investigation team is presenting.

Similarly, the analysis of internal incidents gives an opportunity to analyze incidents from the same organization, the process where the incident occurred and the safety performance of it. The analysis is based on the following criteria: are there any similar incidents? Or is there a significant amount of incidents/near misses in the same unit? The answer to the first question should be followed by a trend analysis and the evaluation of the applicability of previous recommendations into the incident that is being investigated. Conversely, the answer to the second question should be followed by a revalidation of the process hazard analysis for the process where the incident occurred.

Then, the root causes that has been previously determined in this process have to be re-evaluated in order to ensure a complete picture of the analysis in which organizational and cultural flaws can be identified. Subsequently, the required changes in the management system should be identified. This stage of the investigation aims to provide more insights into the identification of root causes and successfully uncover hidden faults of the system and avoid the identification of human error as root causes of the incident. The following step refers to the identification of the technical gaps that have been identified during the investigation. These gaps should be compared with respect to the current training material and provide recommendations to ensure that the training material is up to date and cover all relevant knowledge for each specific role in the organization. The last additional step incorporated into the process refers to the re-evaluation of the leading indicators of the process to determine if the process is showing the right signals, the indicators are well defined and to ensure that operators understand the data and information the system is giving. The main objective of the additional steps is to ensure that root causes are identified and enhance the quality of the recommendations. Finally, the recommendations can be developed, implemented and lessons learned communicated.

6. CASE STUDY

This section analyzes an incident that happened in the offshore industry in North America. The incident has been examined from the perspective of the proposed incident investigation flow chart presented in the previous section. The analysis comprises the analysis of two external incidents with similar causes and two internal incidents that occurred in the same organization. The data and information presented is real and verified. However, data have been anonymized in order to protect the identity of the organization. It should be note that the incident investigation has been performed by the organization at the time where the incident occurred. Therefore, the objective of this analysis is to identify improving opportunities of the final report through the analysis of similar incidents in the industry.

6.1. Incident description

6.1.1. Platform fire and explosion

A high-pressure fuel gas line ruptured on a platform releasing high quantities of high-pressure gas, which detonated within next 5 seconds. The explosion and resulting fire killed 7 people and destroyed a significant part of the platform. The line was designed as a fuel gas separator bypass in order to provide operational flexibility. Thus, the line was used occasionally.

Prior to the incident, the line had been inspected twice, once two years ago and another eight years ago. In both occasions, visual inspection, thickness measurement, and materials characterization were performed. For those inspections, the results were satisfactory and no reduction of the internal thickness was detected, with the exception of a "weldolet" that was changed due to a severe external corrosion. The investigation found that the line rupture was due to a severe localized reduction of the internal thickness of the line. The laboratory analysis determined that the reduction of the internal thickness was the result of a combination of a microbiologically influenced corrosion (MIC) and corrosion associated with high levels of hydrogen sulfide (H_2S).

The identified causes of the incident, associated with prevention and detection of the incident, determined by the organization in the final report are briefly summarized below:

- The fuel gas line was designed assuming that the potential presence of corrosion bacteria was zero
- Bacteria corrosion mechanisms were not considered during the process hazard analysis performed in the unit
- Safety, maintenance, and operational personnel were unaware regarding the presence of bacteria corrosion mechanisms in the platform
- The fuel gas line was designed assuming that there would be insufficient quantities of H_2S in the line to cause significant corrosion
- There was no system in place for real-time monitoring to identify high levels of H_2S in the fuel gas lines of the unit
- The fuel gas line was not identified as a bypass line in the mechanical integrity program to design and perform the corresponding inspection program

- Personnel in the platform were unaware about the responsibility of communicating to the inspectors about bypass lines and dead legs to put special attention during the inspection
- The potential combination of microbiologically influenced corrosion (MIC) and corrosion associated with high levels of hydrogen sulfide (H_2S) was not considered into the corrosion inspection program
- The supervisor in charge did not have the required knowledge to analyze the inspection results given by the inspection company

Based on the identified causes of the incident some of the recommendations are briefly summarized below.

1. Identify and monitor the type, origin, and effect of presented bacteria in the platform and design a tolerance level in order to establish control methods in the fuel gas system
2. Update material selection criteria for fuel gas lines based on the types of damages mechanisms that in combination can influence corrosion velocities
3. Analyze the operational feasibility of eliminating dead legs. Where applicable, implement the use of corrosion inhibitors in the fuel gas system for the corrosion mechanisms mentioned above
4. Ensure the participation of a certified and experienced person in offshore corrosion mechanisms during the development of PHA's
5. Establish communicating procedures of bacteria detection between the platform personnel and inspectors. Additionally, identify all sporadic fuel gas lines in order to

update the inspection program and communicate the required planning and inspection

6. Implement a real-time monitoring system to identify high levels of H_2S in the fuel gas lines of the unit
7. Implement corrosion coupons in the fuel gas system within the offshore platforms
8. Validate H_2S operational limits and evaluate the operational and maintenance strategies for gas processing plants to ensure that permissible levels of H_2S are not exceeded
9. Redesign the corrosion inspection program to ensure that special conditions in the process such as bypass lines and dead legs and combination of corrosion mechanisms such as MIC and H_2S are considered
10. Ensure that all personnel associated with planning, supervision, and execution of activities related to inspection, non-destructive tests, and mechanical integrity are certified and trained based on the applicable national and international regulations (being enunciated but no limit API 570, 572, 510, 574, 580, 581, 653)
11. Develop and/or update static equipment inspection procedures to ensure that they are developed based on the applicable national and international regulations. Additionally, detection and control mechanisms for sporadic lines are included. Finally, detection of corrosion mechanisms associated with the combination of a MIC and corrosion associated with high levels of H_2S
12. Implement additional inspection techniques for the fuel gas lines that allows the identification of corrosion mechanisms such as MIC and H_2S

6.2. Incident analysis

The first step incorporated into the incident investigation process refers to the preliminary analysis in which the significance of the incident is determined. This means to categorize the incident based on the potential impact that the incident may have with the objective of determining the level of detail and complexity of the investigation. In this study, the significance of the incident was determined as very high due to the number of fatalities, injuries and property damaged. Thus, the incident was subject to further analysis during the investigation. The following seven steps were developed during the investigation performed by the organization: report incident, determine the significance of the incident, gather information, develop sequence diagram, identify critical events, identify causal factors, and identify root causes. The next step is the review of previous incidents, which has been developed in this section.

6.2.1. Reviewing external incidents

Review process of previous incidents takes into account two different types of incidents: internal and external incidents. Two incidents were considered for the external incident review process: the first incident is BP North Slope oil spill in 2006 and the second incident is natural gas pipeline rupture and fire in Carlsbad, New Mexico in 2000.

- BP North Slope oil spill, 2006: On March 2nd of 2006, a BP operator discovered a leak in a 34-inch transit pipeline. The leak turned out to be the largest spill ever experienced by Alaskan North Slope. The cause of the leak was due to an internal corrosion that caused a hole at the bottom of the pipeline. The leak was associated with a microbiological corrosion caused by sulfate reducing bacteria [114].

- Natural gas pipeline rupture and fire in Carlsbad, New Mexico, 2000: On August 19th of 2000, a 30-inch natural gas transmission pipeline ruptured. The released gas consequently ignited and burned for almost an hour. The incident killed twelve people and extensively damaged the infrastructure around. The investigation determined that the major safety issues were associated with pipeline design, the internal corrosion control program, the lack of federal safety regulations for natural gas lines, and the inadequate federal oversight [115].

The objective of reviewing external incidents is not only to analyze the applicability of their recommendations to the incident that is being analyzed. It is also to analyze the current practices that others organizations are implementing, compare their technology with respect to others organizations, and extend their existing knowledge regarding national and international standards and best practices that may be applicable to their facilities. Moreover, reviewing external incidents serves as support to explain the causes of the incident to the stakeholders. This means helping build trust and credibility with regard to the results that the incident investigation team is presenting.

6.2.1.1. Corrosion statistics in the offshore industry

The final report of the incident developed by the organization presented a detailed analysis regarding the microbiologically influenced corrosion (MIC) and hydrogen sulfide corrosion (H_2S), supported by laboratory analysis and subject matter experts. However, due to the nature of the combined corrosion mechanisms, the assimilation process from the operators, the supervisor and managers presented a challenge. Even though, the evidence was there, it was hard for them to believe "such unexpected event". Therefore, some representative statistics in the offshore industry has been presented in order to highlight the frequency of this type of incidents in the offshore industry and consequently failure to learn from them.

According to the US Department of Interior Minerals Management Service, almost 3000 offshore pipeline incidents were reported from 1970 to 1999, of which 51% of those were associated with corrosion as shown in figure 20 [116].

Corrosion represents the leading cause of failure in the Gulf of Mexico offshore pipelines, counting for more than 1483 offshore corrosion incidents over the past years. Of these incidents, 35% were associated with internal corrosion and the remaining 65% with external corrosion [116]. Over the period from 1989 to 1999, 75% of the total number of reported corrosion incidents was associated with internal corrosion failures, showing a direct connection between internal corrosion and pipeline aging. Statistics indicates that additional factors such as pipeline infrastructure growing and changes in operating conditions also increase the likelihood of internal corrosion failures [116]. Likewise, statistics show that over the period from 1970 to 1999, the majority of internal corrosion failures occurred in natural gas pipelines, representing 67% (518 incidents) of the reported incidents [116]. Moreover, according with the U.S. Department of Transportation Pipeline and Hazardous Materials Safety Administration, even though the number of reported corrosion incidents in gas gathering lines is not that high, more than 90% of those are caused by internal corrosion failures [117].

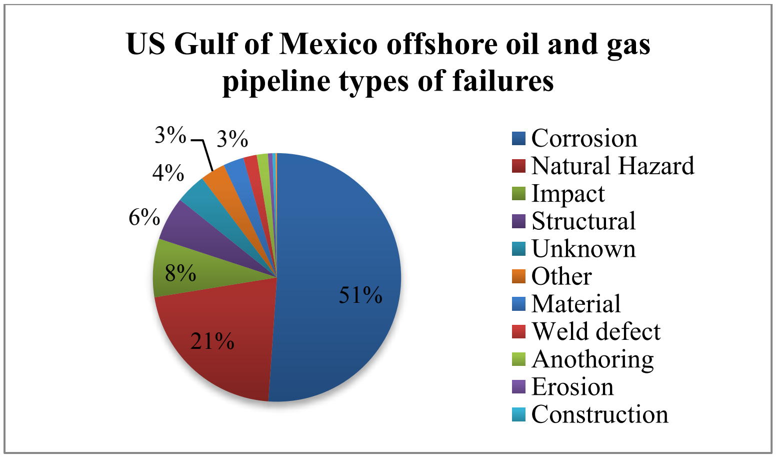

Figure 20 US Gulf of Mexico offshore oil and gas pipeline types of failures over the period from 1970 to 1999, adapted from [116]

6.2.1.2. Corrosion monitoring program

BP North Spill incident report briefly outlined two key aspects that all pipeline corrosion management programs in the oil and gas industry may have such as a corrosion monitoring program and a pipeline leak detection system, which prevent a pipeline from developing leaks and ensuring prompt response once a leak occurs.

At the time of the incident that is being analyzed, the organization did not have an effective internal corrosion-monitoring program for gas lines in place. Likewise, the platform did not have a pipeline leak detection system. The corrosion monitoring program that the organization had at that time involved visual inspection, thickness measurement, and hydrostatic testing. The investigation report recommend the implementation of a real-time monitoring system in order to identify high levels of H_2S and the implementation of corrosion coupons in the fuel gas system. Additional corrosion monitoring system can be considered based on the analysis of the current technology applied for different organizations. For example, BP North Spill incident report highlights the use of “smart pigs” in order to provide more coverage and the detection of smaller defects. Similarly, the investigation report developed by El Paso Natural Gas Company highlights the implementation of ultrasonic testing on the non-piggable portions of the pipeline and the gas quality monitoring to ensure that predefined limits are not exceeded. Furthermore, the report briefly outlined some of the-state-of-the-art technology described by the National Association of Corrosion Engineer (NACE) such as the implementation of Molecular Microbiological Methods (MMM) to monitoring internal corrosion mechanisms in the pipeline. Finally, BP North Spill incident report also emphasizes the technology that was implemented after the incident with respect to their pipeline leak detection system. The organization increased the number of field inspections and implemented infrared heat detectors to improve leak detection.

Based on the results of the previous review of the two external incidents with regards to internal corrosion monitoring program and a pipeline leak detection system, the following recommendations can be incorporated into the final report:

Recomendation1: Evaluate the implementation of the most suitable technology for internal corrosion monitoring in the gas pipeline system. The implementation of smart pigging, ultrasonic testing, and gas monitoring should be analyzed with respect to the existing technology.

Recomendation2: Evaluate the feasibility of the implementation of the-state-of-the-art technology such as molecular microbiological methods in order to monitor bacteria activity.

Aligned with the previous recommendations and some of the recommendations stated in the report, the organization failed to effectively perform a complete management of change program for the incorporation of new technologies or systems into their existing safety management system. Thus, the required resources, expertise, and management commitment were not sufficient to fully prevent and mitigate this type of incident. In this particular case, the organization failed to provide the required training to the personnel in charge of analyzing and providing corrective actions during the inspections that were part of the corrosion-monitoring program. In this sense, even if the inspections were performed based on the schedule, there was a lack of expertise to conclude what was a good or bad result and provide the technical knowledge to determine the following corrective and preventing actions. Moreover, during the inspections performed in the unit, the replaced pieces were never subject to any type of further analysis in order to analyze the identified corrosion mechanism and the potential presence of additional corrosion mechanisms. Thus, bacteria activity and high levels of H_2S were not identified during monitoring activities. El Paso Natural Gas Company incident report discussed some of the post-inspections activities that the organization performed as part of the corrosion-monitoring program. The organization selected some fractions of pipeline that was changed during inspection activities and performed metallurgical examinations to identify additional mechanisms of corrosion.

Based on the previous discussion, the following recommendations can be incorporated into the final report:

Recommendation 3: Enforce the management of change program for the implementation of any new technology or system in which the required training, responsibilities, procedures and channels of communication must be specified.

Recommendation 4: Performed laboratory analysis of some of the portions of pipeline that have been replaced during inspections, in order to identify additional potential mechanisms of corrosion.

6.2.1.3. Applicable standards

The incident investigation report highlights some relevant applicable standards that must be incorporated into employees and contractors training. Likewise, the report recommends the inclusion of those standards into their existing inspection procedures. Those standards mentioned in the report are: being enunciated but no limit, API 570, 572, 510, 574, 580, and 581, 653. However, additional standards can be taken into consideration.

Complementary to the recommendation described in the report, El Paso Natural Gas Company incident report provides a more compressive description of the applicable standards regarding corrosion issues. This can help the organization to expand their knowledge and be aware of more sources of applicable information. Some of the applicable standards are mentioned below:

- NACE SP0106-2006: Internal Corrosion Control in Pipelines
- NACE Standard TM0106- 2006: Detection, Testing, and Evaluation of Microbiologically Influenced Corrosion (MIC) on External Surfaces of Buried Pipelines
- NACE SP0206-2006: Internal Corrosion Direct Assessment Methodology for Pipelines Carrying Normally Dry Natural Gas

- ASME B31.8 Gas Transmission & Distribution Piping
- ASME B31.8S Managing System Integrity of Gas Pipelines
- ANSI GPTC Z380.1 Guide for Gas Transmission, Distribution, and Gathering Piping Systems, 2015 Edition

Additionally, it is important to mention that those standards should not be used only for training and procedures purposes. It is important to verify that the current corrosion management program and internal policies and guidelines are aligned with those applicable standards. Thus, a complementary recommendation can be proposed:

Recommendation 5: Revise and update as required the corrosion management program, policies and internal guidelines in order to ensure that are aligned and comply with all the applicable national and international standards. Some of the applicable standards are mentioned below:

- API 570, 572, 510, 574, 580, 581, 653
- NACE SP0106-2006: Internal Corrosion Control in Pipelines
- NACE Standard TM0106- 2006: Detection, Testing, and Evaluation of Microbiologically Influenced Corrosion (MIC) on External Surfaces of Buried Pipelines
- NACE SP0206-2006: Internal Corrosion Direct Assessment Methodology for Pipelines Carrying Normally Dry Natural Gas
- ASME B31.8 Gas Transmission & Distribution Piping
- ASME B31.8S Managing System Integrity of Gas Pipelines
- ANSI GPTC Z380.1 Guide for Gas Transmission, Distribution, and Gathering Piping Systems, 2015 Edition

6.2.1.4. Corrosion management program

Both external incidents emphasize the main elements involved in any corrosion management program and the required procedures and guidelines that may be in place in order to ensure that effective actions are performed with respect to prevention, mitigation and control. A corrosion management program should clearly address the following elements: definition of policies and objectives, organizational structure and responsibilities, planning, procedures, and implementation, measuring system performance and finally reviewing system performance [91].

Based on the incident report, the investigation revealed that the organization presented weaknesses in their existing corrosion management program. Analyzing some previous incidents in the same platform it can be seen that the platform present failures in their mechanical integrity program in general, not only with respect to corrosion. Although, inspections and corresponding activities are usually performed in accordance with the schedule (implementation phase of the corrosion monitoring program). In their program, some flaws can be identified in the planning and measuring system performance phases. The incident investigation reveals that during the planning phase, not all corrosion threats were identified and the required actions in case of the identification of any failure were not addressed effectively in the program. Likewise, the organization failed to effectively review and analyze the system performance in order to validate the effectiveness of the current corrosion prevention and monitoring methods. Based on this analysis, the following recommendation can be incorporated into the final report.

Recommendation 6: Validate the corrosion management program to ensure that all types of corrosion threats are assessed and a risk assessment is performed. The program should incorporate the following threats: Internal corrosion threat, external corrosion threat, safety/hazard threat, environmental threat and operability threat.

6.2.2. Reviewing internal incidents

For the internal incident review, two incidents were considered. Both incidents occurred on the same platform 3 months and one-year back to the incident that is being analyzed. The incidents were selected based on the criteria of cause similarity and incident unit. Additionally, documents such as previous process safety performance indicators, reliability report, and the mechanical integrity manual, were considered into the analysis.

- Incident 1: A bitter water leak was detected in a 6” line from the low-pressure gas rectifier FA-3104 to the pressurized system, due to a material loss in the line. The line was out of service at the time of the incident. The investigation determined that the leak was caused by severe corrosion in the line. This due to the following causes: presence of trapped water on the line, there was not an action plan in place for removing off-line interconnections, and there was a failure to properly analyze and take actions of the inspections results developed by third parties.
- Incident 2: During maintenance work in a mechanical valve, a minor gas leak was detected in the stem of the valve. The leak was controlled half an hour later. There weren’t any injured, environmental damaged or production losses. The investigation determined that the cause of the incident was due to a deterioration of the stem valve. Additionally, a severe corrosion was detected in the valve.

While reviewing internal incidents, two approaches can be taken as presented in Figure 21. First, analyze if there are a significant number of incidents in the same unit where the incident occurred. The objective of the analysis is to find the need for re-evaluating the process hazard analysis of the process. Secondly, to analyze similar incidents that had occurred in the same organization, to find trends and the applicability of those recommendations to the incident that is being investigated. Finally, the incidents investigation team should go back to the identified root causes and re-evaluate them based on the identified findings.

Even though, there was no record of a significant number of incidents in the same unit. The reported incidents have been classified with high significance. Moreover, the investigation report determined the Process Hazard Analysis (PHA) performed in that process did not consider all different types of corrosion threats that can be present in fuel gas systems. Thus, it is highly recommended to re-evaluate the performed process hazard analysis, analyze those results and provide mitigation actions as required. Moreover, it is important to ensure that is executed by qualified personnel with relevant experience in offshore operations, corrosion mechanisms, and hazard identification methods.

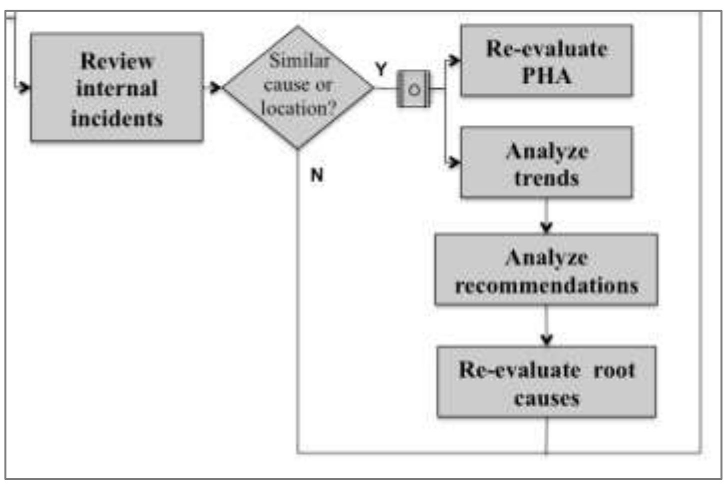

Figure 21 Reviewing internal incidents

In the second part of the analysis, similar incidents with similar causes were considered, along with additional process safety documentation that helped to provide more evidence into the analysis. The following improving opportunities to the existing investigation report were proposed:

Recommendation 7: Re-evaluate the process hazard analysis performed in the fuel gas system of the platform, ensuring that is executed by qualified personnel with relevant experience in offshore operations, corrosion mechanisms, and hazard identification methods.

6.2.2.1. Incident investigation program

A third party hired by the organization was in charge of the development of the investigation report of the incident that is being analyzed. While both the internal incidents reports that were selected for this analysis, were developed by people inside of the organization. Although, the severity of both internal incidents is relatively low compared with the incident for the case study. Some inconsistencies were identified with respect to the level of detail of the analysis, the real identification of root causes, and quality of the recommendations. The analysis exposed that the organization had an inadequate incident investigation program, which inhibits the organization to learn from previous incidents. In this sense, it was unlikely that the organization would prevent a catastrophe like the one in this case study, because the identified causes in previous incidents were limited to the resolution of direct causes such as physical or human causes (changing a valve, replacing a section of the equipment or an employee temporary suspension). Aligned with this, a culture of blame was identified on the previous reports in which some recommendations tended to punish the operator instead of analyzing the causes behind that behavior. Moreover, even if human and organizational causes were identified as root causes of those incidents, the following recommendations were focused just on immediate and physical causes. Hence, flaws were reflected in the incident investigation program and the provided training in this topic. In conclusion, a significant gap was identified between incident investigation reports developed in-house and incident investigation reports developed by a third party.

Recommendation 8: Validate the current incident investigation procedure and methodologies applied by the organization, to guarantee that the identification of root causes is achieved during these processes. Likewise, ensure that the organization has a pool of experts in incident investigation methodologies as well as the overall incident investigation process.

Recommendation 9: Validate and update their current incident investigation training material in order to ensure that the incident investigation process, requirements, and applied methodologies are explained with sufficient detail.

Recommendation10: Ensure the investigation team receives a refreshing training prior any incident investigation, in order to guarantee that people in the team understand the main steps in the process, their role and responsibilities, and the expected outcomes of the investigation.

6.2.2.2. Implementation of recommendations

During the analysis of previous incidents, both incidents emphasize a failure to properly analyze and take actions of the inspections results developed by third parties. The incident used for this case study exposes the same cause in which the supervisor in charge was not able to analyze inspections results due to a lack of knowledge and training regarding this type of data. This is an illustration of how a lack of commitment with respect to the implementation of recommendations can lead to big catastrophes such as the one that is being analyzed. Furthermore, this reflected a lack of enforcement and management commitment regarding the complete achievement of process safety management programs. Thus, even if activities were performed based on the program, no actual actions were performed with respect to the analysis and recommendations of those results, making it hard for the organization to improve and make their processes safer.

Additionally, in incident 1, one of the recommendations suggested the development of an action plan for removing off-line interconnections in the platform. The recommendation was ranked with high priority. Despite the associated risk, the recommendation was never implemented and the same recommendation was identified in the final report of the incident used in this case study.

Recommendation 11: Ensure that recommendations from incident investigations, inspections or audits are easily understood for the operators and supervisor in charge of the process. Likewise, ensure that the personnel in charge of the implementation of those recommendations have the required knowledge and training to interpret this type of information. Moreover, ensure an adequate follow-up program in which the periodic status of recommendations is reported to the management level.

6.2.2.3. Safety management system

In analysis of the internal documentation mentioned previously and the incident in this case study, it can be concluded that there is a lack of proper channels of communications among the different groups of people that interact in the same process. This means, that people in charge of the development of process hazard analysis, inspections, and the daily operators are not aligned with respect of the identified hazards in the process and how they have to work together in order to define the best approach to take for the process. With all things considered, it was concluded that the different elements of the safety management system of the organization do not aligned properly and do not interact with each other. Thus, the mechanical integrity, training or management of change programs are not fully aligned with the process hazard analysis and compliance audits elements of the safety management system in the platform.

Recommendation 12: Ensure that safety management programs of the organization are aligned with the process hazard analysis and audit programs performed in the facility. Ensure appropriate channels of communication, training and qualified personnel to defined effective prevention and mitigation measures.

6.2.3. Identifying changes required in the management system and updating training material

Following the review of previous incidents, the next step in the proposed process is the identification of the changes needed in their management systems, which are exposed during the development of the incident investigation. This stage of the investigation aims to provide more insights into the identification of root causes and successfully uncover hidden faults of the system. Through the analysis of the identified causes of the incident, review of previous internal and external incidents, and an analysis of the current state of their management system, relevant changes in the management system were identified for this case study.

- The analysis suggested that changes in the current training need-matrix are necessary to ensure that personnel have the required knowledge and experience to perform their responsibilities on the platform. This means to validate that the required training for a specific role is up to date and the identified gaps (Corrosion management program, applicable corrosion standards, incident investigation program) are filled by the organization.

- The management of change program should be re-evaluated to ensure that changes in technologies or processes take into account the potential impact on training needs, roles responsibilities, and channels of communications among the organization.
- The mechanical integrity program should be validated to assure that the planning phase of the program is developed for a group of qualified personnel with relevant experience of the process and products in the platform. Likewise, the analysis suggested validating the current personnel selection criteria for the development of process hazard analysis.
- The investigation suggested an overall change in the safety culture of the organization in which the level of engagement and awareness of the top management need to be re-evaluated, as wells as the operational discipline and incident investigation program.
- Within the suggested changed in the safety culture of the organization, the operational discipline program should be re-evaluated in order to ensure that the organization is taking an appropriate approach for communicating and enforcing procedures, standards and policies. Additionally, the audit program must be validated to ensure that the auditors are qualified to perform the job and that audit procedures are adequate, available and understood by employees.
- Together with the two previous arguments, the incident investigation program should be re-evaluated to ensure that appropriate methodologies are applied and that the

incident investigation process, procedures, and roles and requirements are well established and understood.

Aligned with the analysis performed in this step, it is also important to evaluate which training material should be updated based on the technical gaps that were identified during the investigation. For instance, during the development of this case study, technical and organizational gaps such as internal corrosion monitoring program, identification of corrosion threats, and applicable corrosion standards and best practices we identified as current gaps in their training material. Similarly, the incident investigation training material should be validated to ensure that proper methodologies for root cause identification are implemented within the organization and the basis of an effective incident investigation program are covered in this training.

6.2.4. Closing up the process

The next step in the analysis is to re-evaluate the leading indicators of the process where the incident occurred. This with the objective of identifying the fact that if the process is showing the right signals and making sure those operators understand the data and information the system is giving. The case study identified that appropriate indicators were in place. However, performance indicators reports were usually presented without any analysis behind it, making difficult to understand the actual state of the process. The presentation of these indicators was limited to the comparison of the result with respect to the predefined goal of the year. In this sense, the results are presented in a very high level and no analysis of the data was performed. Thus, the learning process cannot be achieved because no actual transformation of the data into information and knowledge is performed. Given these arguments, the following recommendation can be incorporated into the final report.

Recommendation 13: Re-evaluate the objective of the existing leading indicators in the process, in order to verify how the results can help to understand the process behavior and what actions can be taken with respect to these results. Similarly, ensure that performance indicators reports are followed by the corresponding analysis of the obtained results.

Thirteen additional recommendations were developed to the final incident investigation report. Additionally, six changes in the existing management system and the required changes in their current training material were suggested. The recommendations need first to be validated for people inside the organization and the management's approval is required. The next steps in the process are to assign the recommendations and finally share the lessons learned. Those steps are out of the scope of this case study. However, the results are going to be presented to the organization and the following steps will depend on the decision made by them.

6.2.5. The case study into the learning process

The first step in the learning process has been explained to illustrate how incident investigations can be enhanced and quality information can be incorporated into the existing corporate learning system. The following steps in the process require the implementation of a pilot test inside the organization in order to determine the actual performance of the potential alternative and the system. Therefore, a hypothetical case has been developed for one of the recommendations proposed on the previous analysis. The steps two to seven were developed for recommendation 5.

- Second step: acquire information

Enhancing internal information also gives the opportunity to identify additional sources of information that can be used in the future for different facilities or groups of people. In this sense, the selected external incidents (BP North Slope oil spill, 2006 and Natural gas pipeline rupture and fire in Carlsbad, New Mexico, 2000) can be grouped together based on the type of incident or the associated causes (Internal corrosion). Then, this information can be linked to the document management system, so people would have access in case similar information is needed for future investigations or operational inquiries.

- Third step: Assess alternative

During this stage, the corporate learning team identifies the potential scope of the recommendation, the benefits, potential cost, and the associated risk. Based on this analysis, the recommendation would be considered as a potential alternative that should be incorporated across the organization.

- Scope: the recommendation that is being analyzed involves the review of the mechanical integrity program and corrosion guidelines of the platform where the incident occurred. Since some of these documents are transversal for the organization, the initial identification should be performed at a corporate level, follow by the adjustment of internal procedures and implementation of specific activities at a facility level.
- Benefits: the implementation of the alternative would ensure that the organization is operating in a legal and safe manner. In this sense, the organization would implement international corrosion standards, which enables a

consistent interpretation and implementation of the corrosion management program. Likewise, it would support external and internal auditing process to be more consistent with respect to results of inspections and process indicators of the process. Moreover, this would enable the organization to potentially minimize legal liability and be more competitive around the world.

- Cost: the cost would be determined in terms of the number of people required in the initial identification of gaps with respect to the applicable standards and the current corrosion program and guideline, and the cost of a subject matter expert who would serve as an advisory during this phase. Similarly, the time and resources needed to update the documentation, the training required, and finally, the time and resources needed for implementation of specific activities at each facility level.
- Risk: the likelihood of having another similar incident associated with internal corrosion would potentially decrease if appropriate corrosion management guidelines are in place, people are trained, and the documentation is consistently interpreted and implemented within the organization.

For the initial identification, a work team is required. In this team the corporate learning team would work together with three representatives of the process safety department (who are part of mechanical integrity team) and an external subject matter expert with relevant prior experience in corrosion management as well as a strong knowledge in international corrosion standards suggested in this recommendation.

A preliminary plan has been developed to determine how the recommendation would be implemented and the people in charge of the execution of each task. The plan was divided into three phases: identification phase, implementation at a corporate level, and implementation at a facility level. Table 8 to 10 present the preliminary plan for the revision and updating of the corrosion management program and guidelines based on the applicable international standards.

- Fourth step: Define metrics

A set of indicators has been proposed to track the performance and progress of the alternative. The indicators were defined based on the three phases of the action plan.

Identification phase:

- Percentage of standards reviews completed according to the schedule
- Number of non-conformances to non-regulatory corrosion standards per year

Implementation at a corporate level:

- Percentage of activities completed according to the schedule
- Percentage of people trained on the incorporated standards

Implementation at a facility level:

- Percentage of activities completed according to the schedule
- Percentage of people trained on the incorporated standards
- Number of facilities that identified the required changes and developed an action plan
- Number of facilities that performed the required changes
- Number of audits in which the work team participated

- Number of incidents associated with corrosion per year
- Number of repeat non-conformances in all facilities per year
- Number of inconsistencies or issues identified in all facilities during the implementation phase

Table 8 Action plan - Identification phase

Item	**Activity**	**Responsible**	**Timeline**					
			M1	**M2**	**M3**	**M4**	**M5**	**M6**
Identification phase								
1	Review current corrosion management program	Work Team						
2	Review inspection and maintenance guidelines for pipeline systems	Work Team						
3	Review NACE SP0106-2006 and NACE Standard TM0106- 2006	Work Team						
4	Review NACE SP0206-2006 and ANSI GPTC Z380.1	Work Team						
5	Review ASME B31.8 and ASME B31.8S	Work Team						
6	Identify gaps in the current corrosion program and inspection and maintenance guidelines for pipeline systems	Work Team						

Table 9 Action plan - Implementation at a corporate level

Item	**Activity**	**Responsible**	**Timeline**							
			M1	**M2**	**M3**	**M4**	**M5**	**M6**	**M7**	**M8**
Implementation at a corporate level										
7	Update corrosion management program and inspection and maintenance guidelines for pipeline systems	Work Team								
8	Define the appropriate risk tolerance criteria or guidance	Work Team								
9	Perform a management of change process	Work Team								
10	Document sources for potential changes	Work Team								
11	Define technical and regulatory knowledge needed for compliance	Work Team								
12	Define expectations for each facility	Work Team								
13	Define audit schedule to verify compliance	Work Team								
14	Communicate to all appropriate personnel	Work Team								
15	Provide training needed for compliance and auditing	Work Team								

Table 10 Action plan - Implementation at a facility level

Item	Activity	Responsible	Timeline															
			M9	M10	M11	M12	M13	M14	M15	M16	M17	M18	M19	M20	M21	M22	M23	M24
Implementation at a facility level																		
16	Update inspections and maintenance procedures	Each Facility																
17	Perform a management of change process	Each Facility																
18	Provide training needed for compliance of procedures	Each Facility																
19	Perform audits based on schedule	Each Facility																
20	Participate in audits as necessary to ensure that auditors are qualified and verify appropriate information	Work Team																
21	Perform review meeting	Work Team																

- Fifth step: refine alternative

Since the alternative has been designed transversal for all the organization. The execution of the first two phases is required first in order to determine how the alternative is expected to be implemented for each type of facility and consequently determine the specific subtasks required for each of them. For the execution of the third phase, the work team would define the expectations for each facility. This would facilitate the level of detail in auditing and documentation for each facility.

- Sixth step: implement alternative

This step involves the execution of each of the task defined in the action plan. During the first phase of the plan, gaps were identified with respect to the integrity management program elements. More specifically, gaps associated with the integrity threat classification and the identification of the potential pipeline impact by threat. Thus, the standard "ASME B31.8S Managing System Integrity of Gas Pipelines" was the primary source of information for the following phases. During the second phase of the plan, the corrosion management program and inspection and maintenance guidelines were updated, communicated and the mechanical integrity personnel were trained. For the last phase, each facility had to developed a sub plan in which activities such as the reevaluation of the process hazard analysis need to be performed based on the results of the management of change process. Moreover, each facility was in charge of defining the people who need to be trained such as supervisor and operators.

- Seventh step: monitor performance

For the last step of the process, review meetings were scheduled to verify the progress for each facility, identified common difficulties, and analyzed preliminary results of the alternative. Similarly, results of the proposed indicators for the alternative were analyzed, refreshing training was provided and actions were taken based on these results. Finally, the work team participated in some of the audits performed in the facilities in order to verify that auditors are qualified and used the appropriate standards.

This case study was developed with the objective of explaining the proposed incident investigation process and providing a clearer picture of how it can be implemented within the existing incident investigation programs. Moreover, it illustrates how investigations can be enhanced through a more detailed analysis to identify the root causes and consequently achieve high-quality recommendations. Finally, it explains how the case study fits together in the complete learning process through a hypothetical implementation of one of the proposed recommendations.

7. CONCLUSIONS AND FUTURE WORK

7.1. Conclusions

In this thesis, a systemic process for improving learning from incidents has been developed for the chemical and oil and gas industry based on the identified limitations of the learning system. It consists of seven steps that enable organizations to acquire relevant safety information, absorb it and transform it into valuable safety knowledge that can be incorporated into the organizational management systems. The framework is intended to provide a holistic view of the learning from incident process and explore the concept of integration of knowledge management into safety learning systems. Additionally, the limitations of the learning system and the main elements that organizations should take into account to improve learning have been discussed in order to enhance understanding of this field. Finally, the proposed incident investigation process was explained through the development of a case study in which an incident investigation report was enhanced by the identification of improving opportunities for the existing safety management system of the organization.

This work provides a holistic view of the learning from incident process, which comprises the development of a corporate learning system, providing guidelines of how learning systems can be executed within the organization and how to support the implementation of safety knowledge inside of it. The proposed learning process is intended to serve as a tool to disseminate and analyze safety knowledge across the organization. Likewise, it is intended to support single and double-loop learning since it converges a detailed analysis of the underlying causes of incidents, provides the opportunity for analysis from different perspectives and examines of potentially valuable information for the organization. Moreover, the proposed learning system gives some empirical and theoretical insights into the implementation of learning incidents into real organizations for the chemical and oil and gas industry. In this context, the framework aims to provide a more integrated perspective to this field by the incorporation of psychological and engineering inputs into the analysis. Finally, this work give a bigger picture of the learning from incidents process and overcome some of the limitations that the industry faced with regard to this field.

Knowledge management theory has been applied for the purpose of defining the role of safety knowledge in an organization, developing a knowledge culture in which knowledge transfer is encouraged, and finally developing a knowledge structure that incorporated technical and human elements into the system [104]. The study of this research is restricted to enhance internal learning in an organizational level. Therefore, the scope of this thesis was limited to an organizational learning inside the organization. The identified limitations in the learning system have been addressed as follow:

- The implementation of lessons learned and sharing knowledge within the organization have been the focus of this study. Even though, the available literature highlights the importance of sharing and implementing lessons learned [15, 18], the purposes of this study is focused ensuring the implementation of lessons learned in all facilities where it may be applicable, and not just in the facility where the incident occurred. Thus, the implementation of a corporate learning system inside the organization aims to ensure that the lessons learned are not just communicated and disseminated, but also analyzed and documented for all the facilities. Similarly, sharing knowledge within the organization is encouraged in the corporate learning system by the flows of information in and out that are established from and to all facilities that are part of the organization.

- The use and understanding of academic resources and databases are encouraged in the second step of the proposed learning process: acquire information. The identification of external resources has been identified as the key feature of this process in order to get valuable safety information that may be applicable to the organization. Thus, the importance of using databases, external associations, and academic resources has been discussed.
- The identification of root causes is enhanced by the incorporation of additional steps into the traditional incident investigation process. These steps provide some guidelines to the incident investigation team in terms of identifying more insights during the analysis, by the incorporation of additional sources of information that can give more clarity and detail with respect to the organizational, technical and cultural flaws of the organization. Similarly, the proposed process gives a holistic view by the identification of the required changes in the management system and current training material of the organization. Additionally, the proposed incident investigation process encourages the validation of leading indicators of the process in order to ensure that operators and supervisors are getting the right signals to identify technical failures in the system.

The applicability of the proposed process has been explained through the analysis of an investigation report of an incident in the offshore industry. The obtained results provide a clear picture of how the process can be implemented within existing incident investigation programs. Moreover, it explained how investigations can be enhanced through a more detailed analysis in the identification of root causes and how high-quality recommendations can be achieved.

7.2. Future work

Based on the limitations and the scope of this research, the performed study can be complemented by the analysis in the following areas:

- The DIKW (Data, Information, Knowledge, Wisdom) theory has been used in this study in order to leverage the safety knowledge within an organization. The proposed learning process provides a clear understanding of how to transcend data and information into knowledge. However, the concept of wisdom has not yet been clearly defined in this research. Thus, the analysis of why organizations are not getting wisdom, which elements are necessary to achieve it? and analyzing the relationship between learning and wisdom in organizations can be a new area of study in this field.
- The concept of individual learning has been discussed in this research in a high level. Therefore, the necessary elements to achieve individual learning, best approaches to learn, and the relationship between learning and individual

characteristics such as age, motivation, and perception can be further analyzed to understand how these factors can influence the level of retention in individuals.

- The concept of sharing knowledge within the organization has been discussed and how learning systems can be implemented in organizations. However, tools and methods for delivering this knowledge have not been covered in this research. Evaluating the benefits and effectiveness of different types of tools would help organizations to enhance learning at both individual and organizational level.
- A case study was developed to explain how the proposed incident investigation process can be implemented in organizations. Likewise, a theoretical insight was presented of how the case study fits into the complete learning process. The proposed framework of improving learning from incidents should be tested through the development of a pilot in a real organization for a particular group of facilities. This would give the opportunity to validate the complete process and refine it.

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